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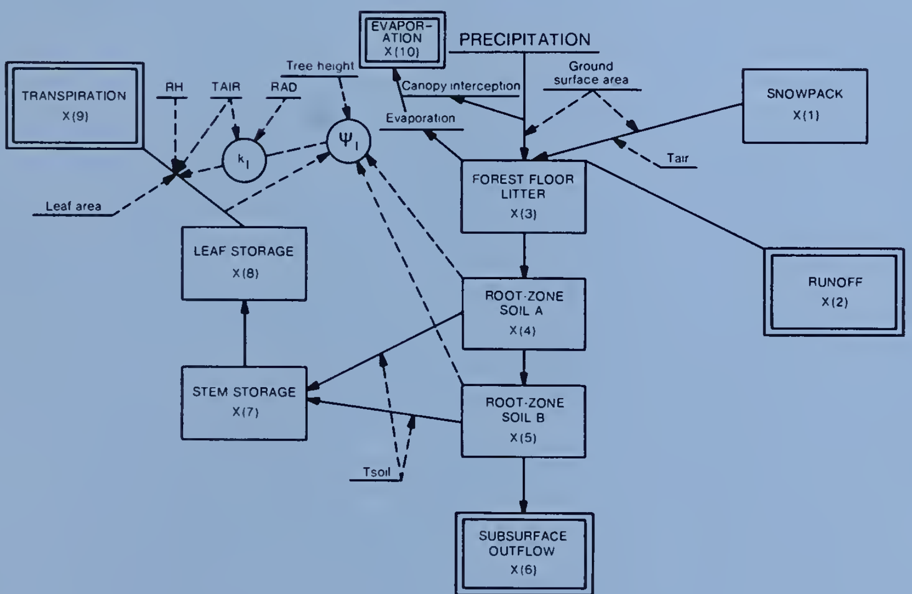
RM-252**

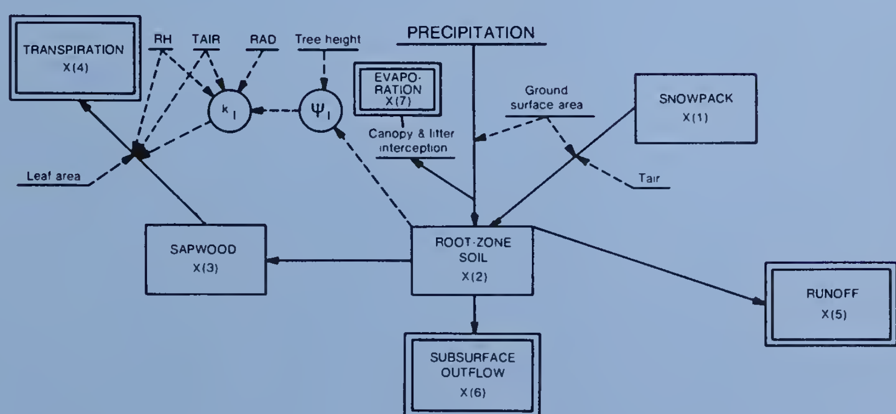
Documentation and Preliminary Validation of H2OTRANS and DAYTRANS, Two Models for Predicting Transpiration and Water Stress in Western Coniferous Forests

Steven W. Running

H2OTRANS



DAYTRANS



Acknowledgements

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Abstract

Two stand-level hydrologic computer models have been developed to study water flow through western coniferous forest ecosystems. The models, H2OTRANS and DAYTRANS, are for hourly and daily timesteps, respectively, and use routine meteorological data. Required parameters include leaf area index, sapwood basal area, and soil storage capacity. The models incorporate rates of snowmelt, precipitation, canopy interception, and litter and soil evaporation. Primary model outputs are transpiration, soil moisture depletion, subsurface outflow, and tree water stress development as measured by leaf water potential and leaf conductance. Complete documentation of all equations is presented, as are the results from an initial validation on lodgepole pine at the Fraser Experimental Forest in Colorado. A sensitivity analysis of the models and a discussion of their range of applicability is also presented.

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INTRODUCTION

Water movement in a forest stand is determined by both physical and physiological factors. A forest ecosystem is diverse in species composition, physical site characteristics, and micrometeorology. Physical factors, such as precipitation, snowmelt, and soil storage provide the water supply, while atmospheric evaporative force generates the demand. In a forest, the tree is a major water transport system from the soil to the atmosphere; this transport system is controlled by physiological responses by the tree to the physical environment.

Some researchers develop stand water use models primarily from a hydrologic perspective (Leaf and Brink 1973). However, recent models of the Soil-Plant-Atmosphere Continuum (SPAC) have blended micrometeorology, hydrology, and physiology. Recent models using this approach have been reported by Sinclair et al. (1976), Tan et al. (1978), Luxmoore et al. (1978), Federer (1979), and Lohammar et al. (1980).

The two models presented in this paper, H2OTRANS and DAYTRANS, have been developed primarily to estimate transpiration and water stress development in western coniferous forests. Earlier development of these models originated primarily from physiological research on stomatal control of conifers under stress (Running et al. 1975, Waring and Running 1976). More recent efforts continued the emphasis on tree-water relations but added more physical processes, such as snowmelt and canopy evaporation, to produce a more accurate model for wider application.

The philosophy of both models considers a stand to be a collection of individual trees. This perspective is necessary because much of the physiological control of water movement in a stand occurs within the tree. A stand is a defined unit, whereas a tree is a biological unit. Consequently, while some parts of the models are stand oriented, such as leaf area index and canopy light attenuation, the models can also be programmed to simulate individual trees. This is not without some difficulty, such as having to estimate lateral rooting distance of an individual tree instead of defining ground surface area as total stand area.

For simplicity the models do not layer the canopy into different compartments or consider vertical or horizontal micrometeorological profiles. A single canopy average is used for meteorological inputs and for computation of physiological responses (i.e., canopy average leaf conductance and leaf water potential). Because the models do not incorporate any terrestrial subunit stratifications, stands must be relatively homogeneous topographically for optimum model performance.

Many of the functions used in the models were developed from research at the Fraser Experimental Forest in central Colorado, working on *Pinus contorta* Dougl. var. *latifolia* Engelm. (lodgepole pine), and from research on *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) in western Oregon.

MODEL DOCUMENTATION

H2OTRANS and DAYTRANS are two process-level compartment simulation models that use climatic, edaphic, and stand data to estimate transpiration, soil moisture depletion, and water stress development in a forest stand. The primary difference between the two models is that H2OTRANS runs on hourly input climatic data while DAYTRANS only requires daily average inputs of climatic data. The most significant outputs from the models are soil moisture depletion, stand transpiration, leaf conductance, and leaf water potential. Compartment diagrams with flow linkages are illustrated in figures 1 and 2.

Both models were constructed using a general simulation processor similar to the FLEX/REFLEX system developed in the IBP Coniferous Forest Biome by White and Overton (1977) for large-scale ecosystem models. Application of the FLEX modeling format also can be found in the description of the CONIFER model of the U.S. IBP Coniferous Forest Biome (CFBMG 1979, Swartzman 1979). The processor assigns all parameters a subscripted variable so that changes in the model can be made easily. State variables or compartments are designated as X(i). The change in X(i) from (t) to (t + 1) is I(i). Flow between state variables is designated F(i, j), where material flows from X(i) to X(j). Driving variables, which typically input climatic variables in ecological models, are Z(i). Constant parameters used in the model are B(i). Finally, intermediate variables used to compute the functions controlling flow in the model are G(i). Other variable notations are given in appendix 1.

The processor is organized as a command program that sequentially calls a set of subroutines containing

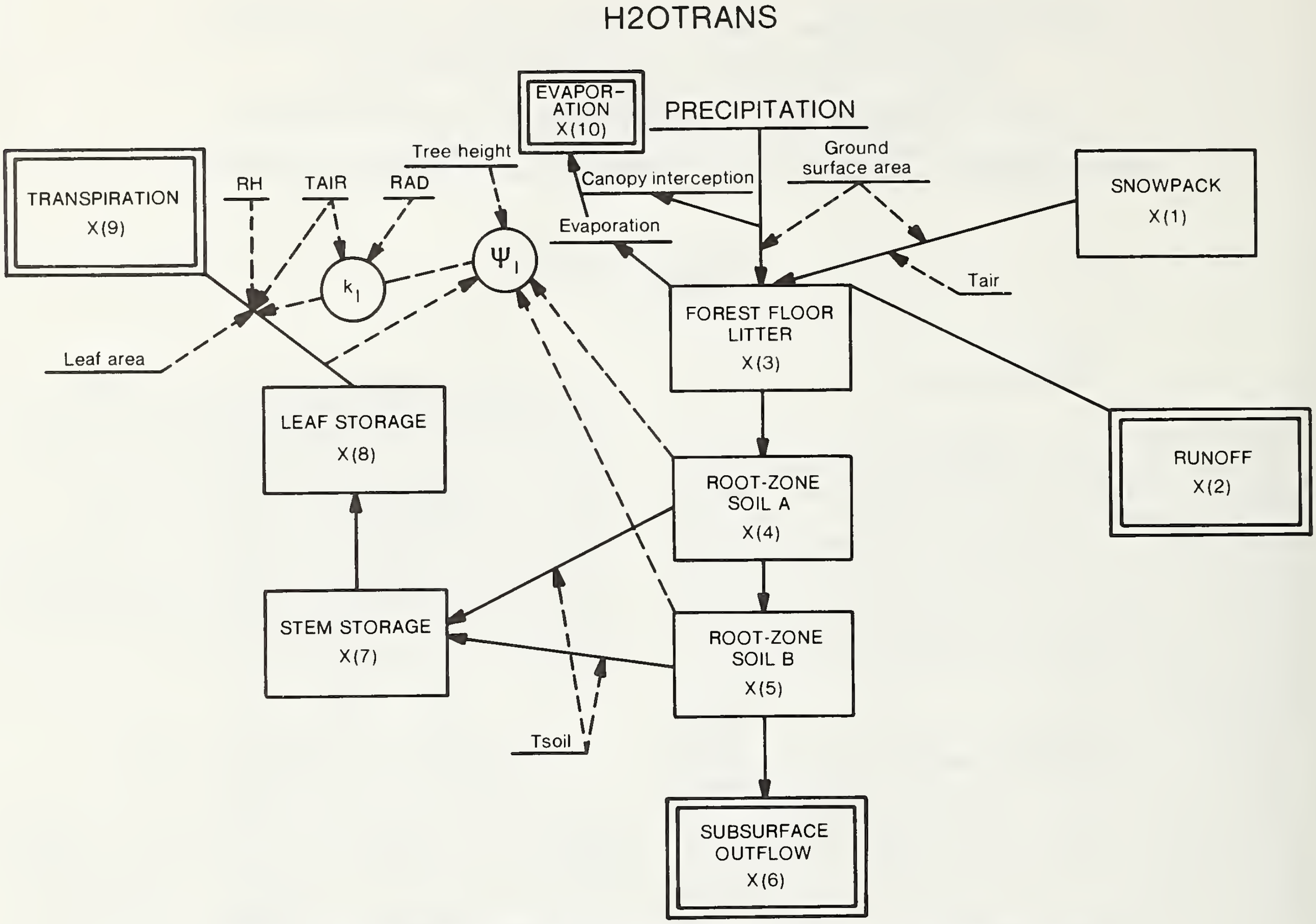

Figure 1.—Compartment diagram and flow linkages for H2OTRANS. The double-lined boxes represent summing compartments.

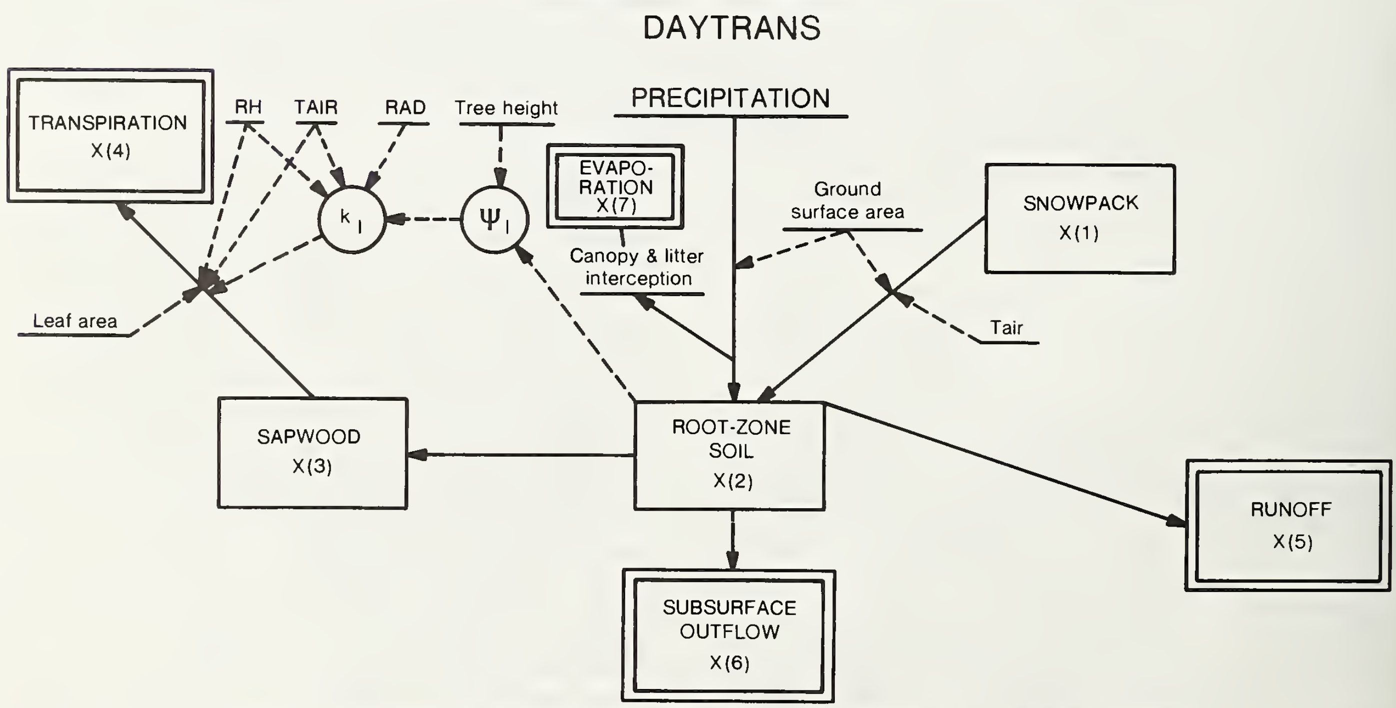

Figure 2.—Compartment diagram and flow linkages for DAYTRANS. The double-lined boxes represent summing compartments.

model detail. The sequence and a brief description of subroutines called follows.

Subroutine	Description
HEADER	Reads in initial information on the number of X, B, G, and Z variables, timestep, and other details that are covered in appendix 2.
ZCOMP	Reads in the Z (driving) variables from a data file, explained in appendix 3.
PROCESS	Calculates all the G (intermediate) variables.
FLOW	Uses the G variables calculated in the PROCESS subroutine to calculate the F (flow) variables, which transfer water between X (state) variables.
YCOMP	Prepares a matrix of computed values for printout.
PRINTER	Labels the line printer page, establishes the output format, and prints out all requested parameters.
UPDATE	Updates the status of the X (state) variables after each iteration by adding or subtracting water as calculated in the FLOW subroutines.
ZERO	Sets the I, Z, F, and G variables to zero after the last iteration in a model run. The last printout then gives a final condition of the X variables.
ERROR	Is a library of error statements called when mistakes are made, which identifies the subroutine that caused problems.

H2OTRANS

STATE VARIABLES—X(i)

State variables or compartments are designated for parts of the stand hydrologic system that have a water storage function. The state of the system can be partially determined by the location of water in the system at any time. Although the state variables give no indication of water transfer in the system, the change in water content of the state variables does. This change is produced by the flow functions described that couple the state variables.

A new state variable can be added to the model by designating a new subscripted X in the header file (appendix 2). The header file then reads the initial conditions for all state variables. Examples of initial conditions for the state variables are given in the Results section. A list and descriptions of state variables follow.

		Unit
X(1) =	snowpack water content	cm^3
X(2) =	soil surface runoff	cm^3
X(3) =	water storage in forest floor litter	cm^3
X(4) =	available root zone water in Soil Level A	cm^3
X(5) =	available root zone water in Soil Level B	cm^3
X(6) =	subsurface outflow	cm^3
X(7) =	stem sapwood water storage	cm^3
X(8) =	leaf water storage	cm^3
X(9) =	transpiration	cm^3
X(10) =	evaporation, canopy and litter surfaces	cm^3

X(1): The snowpack is defined in terms of the water available for melt into the soil. Because growing season water availability is of greatest importance to this model, X(1) is defined when the snowpack is isothermal at 0° C or "ripe" just prior to spring snowmelt. Any additional snowfall is treated as general precipitation by the model and is not added to X(1). This was done to avoid having to deal with the volume of information needed to calculate an energy budget for the snowpack as developed by Leaf and Brink (1973). Although this simplified snowpack definition is not an accurate estimator of snowpack dynamics, on most years it should be adequate to follow snowmelt into the soil.

X(2): An unlimited summing compartment for surface runoff water that occurs when precipitation or snowmelt exceeds the soil surface infiltration capacity.

X(3): The water content of the forest floor litter. Although this is a small component of the stand water balance, the water content of the forest floor litter is a critical factor in litter decomposition rates, an important part of the terrestrial nutrient cycle.

X(4), X(5): The soil water supply available to the roots is partitioned between X(4) and X(5). Rooting depth and lateral extent must be estimated to compute the total volume of soil tapped by the root systems. While approximate estimation of X(4) and X(5) for a stand is not difficult, exact measurement of these compartment sizes for an individual tree is laborious. X(4) is defined as the upper 50% of the root zone and X(5) as the lower 50%, although this distribution can easily be changed. The main purpose for splitting the root zone water into two compartments was to provide the option of simulating competition between plants of different rooting depth.

X(6): An unlimited summing compartment for water that percolates below the rooting zone. This compartment only receives water when input precipitation or snowmelt continues after X(3), X(4), and X(5) have been filled.

X(7): The water available for transpiration from the stem sapwood of the trees.

X(8): Water stored in the leaves (needles) available for transpiration. This source is small when compared to the rest of the tree water system, but it directly determines leaf water potential (ψ_l). Therefore, it is critical in the control of stomatal response and leaf conductance (k_l).

X(9): Cumulative transpiration from the tree or stand.

X(10): Cumulative evaporation from the stand canopy and litter surfaces.

At each iteration, the current status of each state variable X(i) is printed. In addition, the net change in each state variable from the previous iteration is also printed, designated I(i). For example, X(9) is cumulative transpiration since the beginning of the simulation, and I(9) is the transpiration that occurred in the previous 1-hour timestep.

FLOW FUNCTIONS—F(i,j)

The convention of F(i,j) is that X(i) is the state variable from which water is withdrawn; X(j) is the compartment to which water from X(i) is added. If i = j, this denotes water input from a source external to the model entering X(i) or output to an unmonitored sink. The F(i,j) notation couples the correct state variables, while the G variables shown are the calculated magnitude of flow between X(i) and X(j) at any iteration. The equations used to calculate the G variables are described in a subsequent section. A list and descriptions of flow functions follow.

	Unit
F(3,3) = G(50) – G(53)	cm^3
F(1,3) = G(51)	cm^3
F(3,2) = G(54)	cm^3
F(3,4) = G(55)	cm^3
F(4,5) = G(56)	cm^3
F(5,6) = G(57)	cm^3
F(8,9) = G(18)	cm^3
F(7,8) = G(62)	cm^3
F(4,7) = G(67)	cm^3
F(5,7) = G(68)	cm^3
F(10,10) = G(53) + G(58)	cm^3

F(3,3): Precipitation into the model from the exterior source (driving variable) minus canopy interception that does not reach the forest floor. Also subtracts litter surface evaporation from X(3).

F(1,3): Snowmelt input to the forest floor litter compartment.

F(3,2): Surface runoff that occurs when precipitation and/or snowmelt exceeds the soil surface infiltration capacity.

F(3,4): Water that flows into the root zone Soil A compartment, X(4), after the forest floor litter is saturated (i.e., after X(3) is at capacity).

F(4,5): Water that enters after X(4) has reached capacity is cascaded to X(5).

F(5,6): When X(3), X(4), and X(5) are all at capacity, additional water input to the system is routed to subsurface outflow, X(6), from X(5).

F(8,9): Moves water from leaf storage, X(8), to the transpiration sink, X(9).

F(7,8): Water withdrawn from internal tree sapwood storage to help satisfy the water demand generated by F(8,9) and the deficit created in X(8).

F(4,7), F(5,7): When a water deficit is created in X(7) by transpiration, F(8,9), this demand is met by root water uptake from the two rooting zone soil reserves, X(4) and X(5).

F(10,10): Canopy and litter evaporation.

Note that water movement into the soil state variables, X(1) through X(6), is basically input or donor controlled. Water withdrawal from the system, (transpiration) is an output demand with donor control.

DRIVING VARIABLES—Z(i)

These variables are input from an exterior data file. Appendix 3 presents this data file format. Precipitation and soil temperature are input once every 24 hours; the other meteorological variables are entered hourly. This was done because precipitation is rarely recorded more than once daily by most installations, and soil temperature at 20 cm changes slowly. The 24-hour precipitation is input into the model as 1/4 of daily total at hours 1, 2, 3, and 4 of each day. This limits the effects of short but severe thunderstorms. In particular, surface runoff, F(3,2), rarely occurs. Precipitation could easily be input hourly, and I recommend this modification, if hourly data can be recorded. The other variables either can be recorded once each hour, typically on the hour, or be full-hour averages. A list of driving variables follows.

	Unit
Z(1) = Julian date	day
Z(2) = precipitation	cm day^{-1}
Z(3) = air temperature	°C
Z(4) = relative humidity	%
Z(5) = soil temperature (20 cm depth)	°C
Z(6) = incoming shortwave radiation	ly min^{-1}
Z(7) = hour of day	h

AUXILIARY CONSTANTS—B(i)

The constant parameters are values entered into the model for use in various computations; they do not change throughout the model run. These can include stand physical dimensions, conversion constants, and empirical coefficients used to calculate intermediate (G) variables. All B parameters are specified and entered into the program by the HEADER file, explained in detail in appendix 2. Examples and derivations of values used for the B constants are covered in the Results section because many are site-specific. A list of auxiliary constants follows.

	Unit
B(1) = snowpack melt coefficient	cm $°C^{-1}$
B(2) = maximum soil surface infiltration rate	cm h^{-1}

B(3) =	water storage capacity of forest floor litter, X(4)	cm^3
B(4) =	maximum available water storage in root zone Soil A, X(4)	cm^3
B(5) =	maximum available water storage in root zone Soil B, X(5)	cm^3
B(6) =	canopy interception coefficient	cm LAI^{-1}
B(7) =	maximum available water storage in stem sapwood, X(7)	cm^3
B(8) =	maximum available leaf water storage in X(8)	cm^3
B(9) =	tree or stand total leaf area (not projected area)	cm^2
B(10) =	ground surface area	cm^2
B(11) =	average midcrown tree height	m
B(12) =	maximum canopy average leaf conductance (k_l)	cm s^{-1}
B(13) =	spring minimum predawn leaf water potential ($B\psi_l$) NOTE: Throughout the model, water potential is treated as a positive value for mathematical simplicity.	MPa
B(14) =	leaf osmotic potential (and stomatal closure threshold)	MPa
B(15) =	sapwood basal area	cm^2
B(16) =	leaf water depletion coefficient	h^{-1}
B(17) =	stem and soil water exchange coefficient	h^{-1}

INTERMEDIATE VARIABLES—G(i)

The intermediate variables are used for a variety of preliminary calculations in the model. Because each flow variable is controlled by many factors, it is not possible to write one equation representing all conditions. Consequently, G variables are used to provide more manageable intermediate computations. Often the G variables will represent specific processes of importance in the model, such as the control of leaf conductance by incoming radiation. Because all G variables have a unique subscript, they do not have to be used sequentially. For clarity it is useful to group G variables that are performing similar computations. A brief index of G variables precedes their detailed documentation.

G(1) - G(9):	water storage and water content calculations
G(10) - G(19):	leaf conductance and transpiration calculations
G(50) - G(59):	soil water input calculations
G(60) - G(69):	tree water uptake calculations
G(70) - G(79):	leaf water potential, flow resistance T/PT ratio.

Description of G Variables

Water Storage and Water Content

G(1) = absolute humidity deficit (g cm^{-3})

$$G(1) = S3(Z(3), Z(4))$$

where
Z(3) = air temperature,
Z(4) = relative humidity.

This statement sends air temperature and relative humidity to Function S3. The function calculates absolute humidity deficit and returns it to G(1).

G(2) = leaf area index, LAI (m^2 m^{-2})

$$G(2) = B(9)/B(10)$$

where
B(9) = total stand (or tree) leaf area, all surfaces,
B(10) = total stand (or tree) ground surface area.

G(3) = available water fraction in X(3), forest floor litter (cm^3 cm^{-3})

$$G(3) = X(3)/B(3)$$

where
X(3) = present water content of the forest floor litter,
B(3) = water capacity of the forest floor litter.

Converting available water in compartments to a fraction allows easy changing of compartment sizes through the Header file without reprogramming each G variable.

G(4) = available water fraction in X(4), the upper soil root zone (cm^3 cm^{-3})

$$G(4) = X(4)/B(4)$$

where
X(4) = present water content of the upper soil root zone,
B(4) = water capacity of the upper soil root zone.

G(5) = available water fraction in X(5), the lower soil root zone (cm^3 cm^{-3})

$$G(5) = X(5)/B(5)$$

where
X(5) = present water content of the lower soil root zone,
B(5) = water capacity of the lower soil root zone.

G(6) = averaged available water fraction in the total soil rooting zone (cm^3 cm^{-3})

$$G(6) = (G(4) + G(5))/2$$

where
G(4) = available water fraction in the upper soil root zone,
G(5) = available water fraction in the lower soil root zone.

G(7) = available water fraction in X(7), stem storage (cm^3 cm^{-3})

$$G(7) = X(7)/B(7)$$

where
X(7) = present stem sapwood water content,
B(7) = maximum available stem sapwood water storage.

Leaf Conductance and Transpiration

G(10) = predawn leaf water potential, $B\psi_l$ (–MPa)

$$G(10) = AMAX1\ (B(13),\ 0.2/G(6) + 0.01 \cdot B(11),\ 0.0)$$

where
AMAX1 = an intrinsic FORTRAN function that chooses the maximum from a set of values in the parentheses,
B(13) = spring minimum predawn leaf water potential,
0.2 = an empirical coefficient used to generate the curve in figure 3,
G(6) = averaged total available water fraction,
0.01 = hydrostatic gradient constant (MPa m^{-1}),
B(11) = midcrown tree height.

This statement calculates the predawn leaf water potential ($B\psi_l$) as a function of available root zone soil water in X(4) and X(5) (fig. 3). This type of relation between $B\psi_l$ and soil water content has been found numerous times in various plant communities (Sucoff 1972, Hinckley and Ritchie 1973, Branson et al. 1976, Huzulak 1977). The function basically combines the well-known curvilinear relationship between soil water content and soil water potential (Heth and Kramer 1975, Nnyamah and Black 1977), and the linear relationship between soil water potential and predawn leaf water potential (Hinckley et al. 1978, Drew and Ferrell 1979, Sala et al. 1981).

This treatment of the soil-plant interaction is rather superficial and yet, appears adequate for the purposes of this model. Implicit in the equation is the moisture tension release curve of a well-drained sandy loam. The equation would not easily incorporate a soil of radically stratified physical characteristics. In that instance, it would be best to define separate soil compartments (X(4), X(5), etc.) and treat each soil horizon individually.

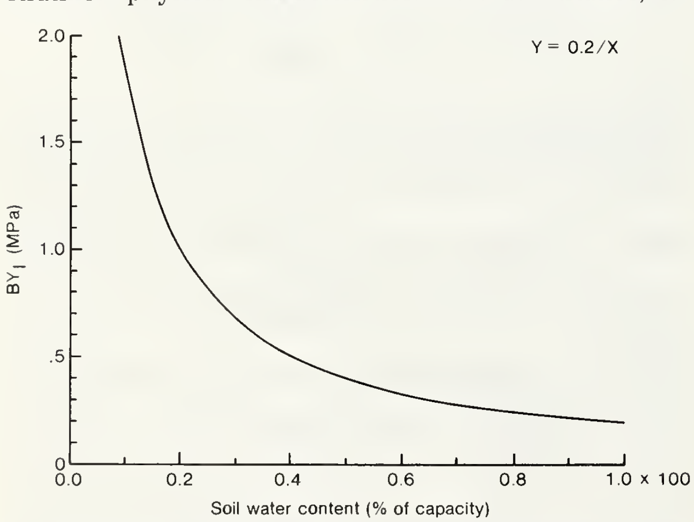

Figure 3.—The function relating soil water content (percent of field capacity) to predawn leaf water potential, $B\psi_l$ (an estimate of soil water potential).

This equation also assumes root distribution adequate to extract water from the entire defined rooting zone soil compartment. Consequently, both the definition of available water in rooting zone soil (X(4) and X(5)) and a correct response function for G(10) (fig. 3) is necessary for the model to correctly predict the magnitude and timing of soil moisture depletion and tree water stress development. For accurate results, this response curve (fig. 3) should always be checked in a new area with field measurements of predawn leaf water potential plotted against soil water content.

G(11) = light-saturated leaf area index ($m^2\ m^{-2}$)

$$G(11) = 10.0 \cdot (1.0 - EXP(-4.6 \cdot Z(6)))$$

where
10.0, 1.0, –4.6 = curve-fitting coefficients,
EXP = exponential,
Z(6) = incoming shortwave radiation.

Stomata of many trees do not fully open until incoming shortwave radiation reaches around 10% of full sunlight (Davies and Kozlowski 1974, Dykstra 1974, Hinckley et al. 1975, Watts et al. 1976, Hinckley et al. 1978). So, G(11) calculates how much leaf area index is above the radiation threshold of 0.1 ly min^{-1} at the current radiation level Z(6). A typical Beer's Law exponential decrease in radiation as it passes vertically through the canopy is assumed (fig. 4). The most difficult and least measured parameter is the attentuation coefficient of radiation as it penetrates different forest canopies (Norman and Jarvis 1975, Jarvis et al. 1976). I used an attenuation analysis from Kira et al. (1969), also used by J. Rogers (pers. comm.) in his general watershed hydrologic model for the IBP Coniferous Forest Biome. Note that his analysis attenuates radiation as a function of LAI, not vertical height, eliminating need for data about canopy geometry. However, implicit in this treatment is the assumption of a relatively continuous canopy. A semiopen stand of large trees may have deep canopies but an overall low stand LAI. Also, no attempt is made to adjust radiation effects for diurnal sun-angle changes as is done in more rigorous canopy radiation models (Norman and Jarvis 1975).

G(12) = k_l, radiation correction fraction (dim.)

$$G(12) = 1.0 - (G(2) - G(11))/G(2)$$
$$IF(G(11)\ .GT.\ G(2))\ G(12) = 1.0$$

where
1.0 = unity multiplier for k_l reduction,
G(2) = leaf area index,
G(11) = light-saturated leaf area index,
.GT. = a FORTRAN statement, "greater than."

If the light-saturated leaf area index calculated in G(11) is larger than the actual LAI of the stand, then no light-induced k_l reduction occurs, and G(12) computes a 1.0 multiplier for k_l. If light is limited to a portion of the canopy, G(12) calculates what fraction of the stand LAI is light-saturated and uses that fraction as a multiplier for the k_l final calculation. Consequently, if 70% of the canopy is receiving 0.1 ly min^{-1} or greater, radiation k_l is multiplied by 0.7 to reduce the canopy average

because of the canopy that has closed stomata. Note that this assumes a $k_l = 0$ for leaves under the radiation threshold, but more precise estimates of k_l at low-light levels would become complicated and would exceed our knowledge of canopy light attenuation theory and short-term stomatal fluctuations under low-light conditions.

G(13) = k_l, predawn leaf water potential correction (cm sec^{-1})

G(13) = AMAX1 (B(12) – (B(12)/(B(14) – B(13)))·(G(10) – B(13)),0.005)
IF(G(10) .LT. B(13)) G(13) = B(12)

where
B(12) = maximum canopy average k_l,
B(13) = spring minimum predawn leaf water potential,
B(14) = stomatal closure threshold,
G(10) = predawn leaf water potential, $B\psi_l$,
0.005 = k_l at complete stomatal closure,
LT = a FORTRAN statement "less than."

This function reduces maximum k_l as soil water is depleted (fig. 5). Maximum daily k_l has been found to be a direct function of $B\psi_l$, G(10). This function was first demonstrated on *Pseudotsuga menziesii* in Oregon by Running (1976) and duplicated on *Pinus contorta* in Colorado by Running (1980), both on sapling-size trees. Although I hypothesize that the relationship between $B\psi_l$ and maximum k_l is fundamental, different species and different tree sizes may require a modified response curve. Consequently, B(12), B(13), and B(14) were made externally changeable. The ratio B(12)/(B(14)-B(13)) provides the slope of the k_l reduction for any range of k_l and B(14) entered.

The 0.005 cm s^{-1} minimum k_l has been generally found for a variety of conifers (Hinckley et al. 1978). It should be remembered that the k_l value calculated here represents a canopy average for leaves of different ages through all crown heights.

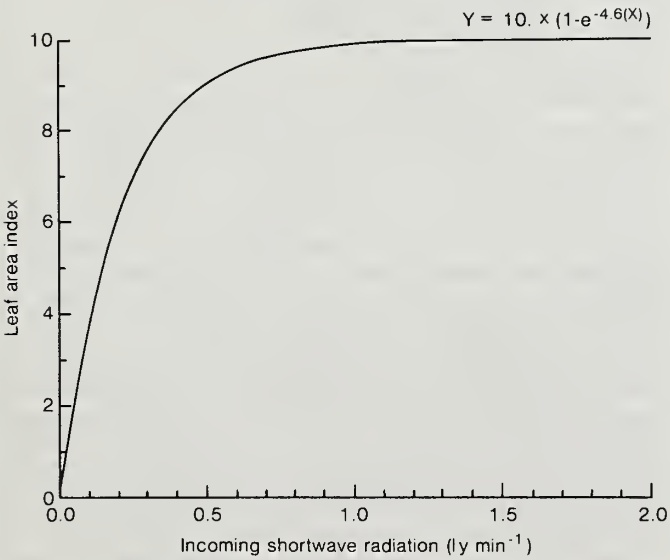

Figure 4.—Describes the leaf area index, LAI, that would receive incoming shortwave radiation in excess of 0.1 ly min^{-1} (the stomatal opening threshold) at any level of incoming radiation.

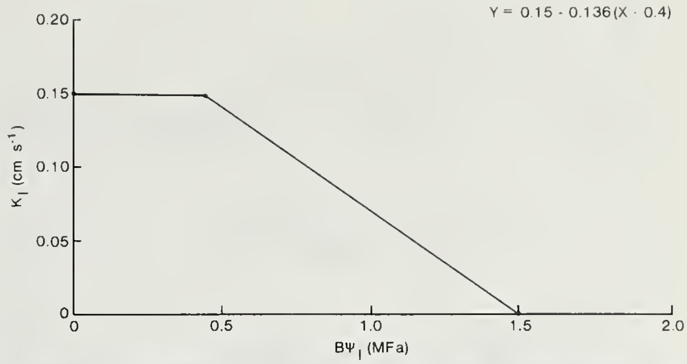

Figure 5.—The reduction in maximum leaf conductance, k_l, resulting from increasing plant water stress (predawn leaf water potential, $B\psi_l$).

G(14) = k_l, humidity correction (cm s^{-1})

G(14) = G(13) – (G(13)·0.05·(G(1)·10^6 – 4.0))
IF(G(14) .LE. 0.0) G(14) = 0.005

where
G(13) = k_l, leaf water potential correction,
0.05 = k_l, humidity deficit slope coefficient (fig. 6),
G(1) = absolute humidity deficit,
4.0 = initial humidity reduction threshold (μg m^{-3}),
.LE. = a FORTRAN statement, "less than or equal to,"
0.005 = minimum k_l.

There is much evidence that k_l is reduced by low atmospheric humidity, regardless of ψ_l. As absolute humidity deficit calculated in G(1) increases, the maximum k_l from G(13) is linearly reduced as a fraction of the original (G(13)) leaf conductance. Theoretical analysis of this phenomenon is reported in Lange et al. (1971), Sheriff (1977), Edwards and Meidner (1978), and Losch and Schenk (1978). The function in G(14) is based on field data on western conifers reported by Running (1976, 1980), Kaufmann (1976), and Tan et al. (1977).

From reviewing the above papers, Running (1980) found that this function reasonably represents field data collected on *Pseudotsuga menziesii*, *Pinus ponderosa*, *Pinus contorta*, *Picea sitchensis*, *Picea engelmannii*, and *Tsuga heterophylla*. It appears that when humidity reduction in k_l is analyzed as a fraction of daily maximum k_l, a fairly generalized equation, such as in G(14), can be developed.

Note that with this equation structure the G(14) equation is independent of maximum k_l, which is input from B(12) through G(13). Also, at an absolute humidity deficit above 25 μg cm^{-3}, the second equation sets k_l = 0.005 cm s^{-1}, a general minimum leaf conductance substantiated by many studies. Trees in very arid climates may be able to retain stomatal opening at these humidity deficits.

G(15) = k_l, air temperature correction (cm s^{-1})

G(15) = S1(Z(3), Z(7),G(14))

where
S1 = a special function called from elsewhere in program that uses Z(3), Z(7), and G(14) values to calculate G(15),

Z(3) = air temperature,
Z(7) = hour of day,
G(14) = k_l, humidity reductions.

This equation calls special function S1 where the effect of air temperature of k_l is calculated and returned as G(15).

G(16) = k_l, final canopy average (cm s^{-1})

$$G(16) = G(15) \cdot G(12)$$

where
G(15) = k_l,
G(12) = radiation limiting fraction.

This computes the final canopy average k_l by the radiation reduction fraction from G(12).

To summarize k_l control in the model: G(13) computes leaf (and soil) water potential effects. G(14) adds humidity effects to k_l. G(15) adds air temperature effects. Finally, G(16) adds radiation control from G(12). The overall hierarchy of k_l control from strongest to weakest is (1) radiation, (2) leaf water potential or $B\psi_l$, (3) humidity or ABSHD, and (4) air temperature.

G(17) = transpiration flux density (g cm^{-2} s^{-1})

$$G(17) = G(16) \cdot G(1)$$

where
G(16) = k_l, canopy average,
G(1) = absolute humidity deficit (ABSHD).

Transpiration flux density is the product of k_l and ABSHD. This equation is equivalent to the diffusion equation used by Tan et al. (1978).

$$E = (PCp/LV)((e_s - e_a)/(r_s + r_a))$$

where
E = transpiration rate (g cm^{-2} s^{-1}),
P = air density (g cm^{-3}),
Cp = specific heat of air (J g^{-1} $°C^{-1}$),
L = latent heat of vaporization (J g^{-1}),
V = psychrometric constant (mb $°C^{-1}$),
e_s = saturation vapor pressure (mb),
e_a = ambient vapor pressure (mb),
r_s = stomatal resistance (s cm^{-1}),
r_a = aerodynamic resistance (s cm^{-1}).

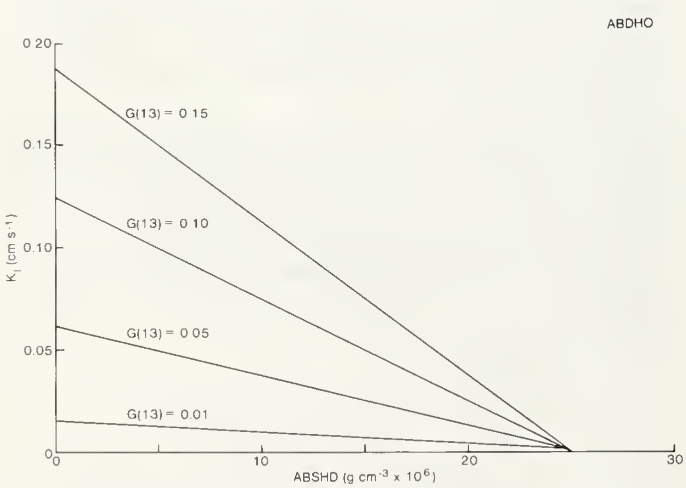

Figure 6.—The reduction in maximum leaf conductance, k_l, resulting from increasing absolute humidity deficit.

In the equation in G(17), P, Cp, L, V, e_s, and e_a are all subsumed into G(1), the absolute humidity deficit. Both Tan et al. (1978) and the research reported here ignored r_a for the reason that r_a is typically 20-100 times smaller than r_s in coniferous forests (Smith 1980), and would require input of vertical profiles of windspeed. Also, k_l = $1/r_s$ is used.

Midday humidity in western forests is so low that the humidity deficit component of the Penman - Monteith equation far exceeds the radiation component of evaporative demand (Jarvis et al. 1976, Luxmoore et al. 1981). Consequently, the diffusion equation used in G(17) to compute stand transpiration and used by Tan et al. (1978) in their transpiration model varies from the more theoretically satisfying Penman - Monteith equation by less than 2%. The diffusion equation is used because of its simplicity and reduced demand for meteorological input variables.

G(18) = hourly stand transpiration (g h^{-1})

$$G(18) = G(17) \cdot B(9) \cdot 3600$$

where
G(17) = transpiration flux density,
B(9) = stand leaf area,
3600 = seconds per hour.

G(18) equals F(8,9), water transfer from leaf storage, X(8), to the atmospheric transpiration sink, X(9).

Soil Water Input

G(50) = effective precipitation (cm^3 h^{-1})

IF(Z(7) .GT. 4.) Z(2) = 0.0
G(50) = AMAX1((Z(2)/4–B(6)·(B(9)/B(10)))·B(10),0.0)

where
Z(7) = hour of day,
Z(2) = precipitation,
B(6) = canopy interception coefficient,
B(9) = stand leaf area,
B(10) = ground surface area.

This function translates the one-dimensional precipitation data into volumetric units and subtracts canopy interception based on leaf area index, B(9)/B(10). The result is equal to F(3,3), the precipitation input into X(3).

Precipitation Z(2) is divided by 4 to estimate input from the once-daily precipitation record and is entered between 0000 and 0400 hours. This may underestimate instantaneous rainfall intensity and overestimate interception losses. With modern data-loggers, hourly precipitation should be recorded to avoid these artificial problems. Canopy interception of precipitation is treated proportionally to LAI using an interception coefficient which, in effect, is leaf surface water storage. Nearly two-thirds of the annual precipitation in a Rocky Mountain lodgepole pine forest falls as snow, outside of the growing season (Alexander and Watkins 1977). Summer rainfall typically is in the form of short thundershowers that do not recharge the rooting zone soil and are a modest component of the stand hydrologic balance. Consequently, while more elaborate canopy in-

terception and evaporation models are available (Rutter et al. 1971, Murphy and Knoerr 1975, Stewart 1977, Ford and Deans 1978), a more accurate treatment of interception processes does not seem warranted here. This algorithm assumes that the canopy is dry at each hourly iteration, which overestimates interception loss during an extended rainfall event. Also, no attempt is made to retard transpiration while the canopy is wet. However, this problem is reduced implicitly because, after a thundershower, evaporative demand is greatly reduced until the intercepted water has evaporated.

Application of this model to sites having more significant summer precipitation should entail collecting hourly precipitation data and possibly calculating a canopy energy balance to predict evaporation of intercepted precipitation.

The AMAX1 function with a 0.0 limit is used to protect the equation from calculating a negative precipitation.

G(51) = snowmelt ($cm^3\ h^{-1}$)

G(51) = AMIN1(Z(3) · B(1) · B(10), X(1))
IF(Z(3) .LE. 0.0) G(51) = 0.0

where
Z(3) = air temperature,
B(1) = snowpack melt coefficient,
B(10) = ground surface area,
X(1) = snowpack water content.

This equation melts the snowpack in X(1) as a function of air temperature, Z(3), and a melt coefficient, B(1), then multiplies it by ground area, B(10), to give volumetric water input to X(3). The degree-day snowmelt equation was basically derived from data in the U.S. Army Corps of Engineers Snow Hydrology report (1956). This approach is only reasonable for spring snowmelt of a ripe isothermal pack. More rigorous models of snowmelt do complete energy balances for the snowpack (Leaf and Brink 1973, Colbeck and Ray 1979). This increased complexity seems unnecessary for a model whose focus is primarily summer water stress development. The melt coefficient, B(1), should be recalibrated for use in other regions. G(51) is equal to F(1,3).

G(52) = litter vapor conductance ($cm\ s^{-1}$)

G(52) = EXP(5.0 · (G(3) − 1.0))

where
5.0, 1.0 = curve-fitting coefficients,
G(3) = litter water fraction.

This equation calculates a water vapor conductance term for evaporation of water from the forest floor litter. My approach is derived from classic evaporation and diffusion principles (Lee 1980), and is similar to the litter evaporation function of CFBMG (1979), except that a variable conductance term, G(52), was calculated as a function of litter water content. It assumes a conductance of 1.0 cm s^{-1} from a saturated litter layer, with an exponential decrease in conductance as the litter surface dries, increasing boundary layer resistance (fig. 7).

G(53) = litter evaporation ($cm^3\ h^{-1}$)

G(53) = G(52)·G(1)·B(10)·3600
IF(G(3) .LE. 0.0) G(53) = 0.0
IF(X(1) .GT. 0.0) G(53) = 0.0

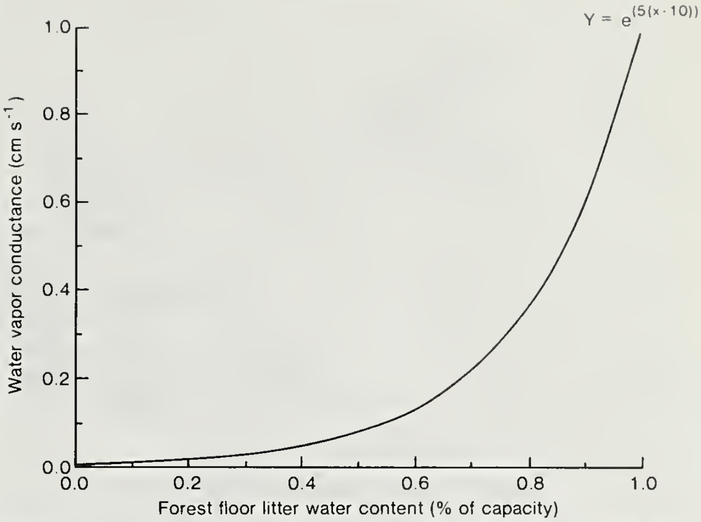

Figure 7.—As water content of the forest floor litter is depleted, the water vapor conductance is reduced by this function.

where
G(52) = litter vapor conductance,
G(1) = absolute humidity deficit,
B(10) = ground surface area,
3600 = seconds per hour,
G(3) = litter water fraction,
X(1) = snowpack water content.

Litter evaporation is driven by atmospheric demand, absolute humidity deficit, G(1), and is limited by G(52) as the surface dries. Volumetric litter evaporation per hour is determined by multiplying by B(10) and 3,600 s/hour. This approach is simple and can be calibrated easily. Model adjustments would best be made in the G(52) response curve of figure 7. Because this equation only quantifies mass transfer considerations of evaporation theory, water loss from an open surface subjected to a significant diurnal radiation load may be underestimated. G(53) is subtracted from the water input to X(3) by F(3,3).

G(54) = surface runoff ($cm^3\ h^{-1}$)

G(54) = AMAX1((G(50) + G(51)−(B(2)·B(10))), 0.0)

where
G(50) = precipitation,
G(51) = snowmelt,
B(2) = maximum soil surface infiltration rate,
B(10) = ground surface area.

If precipitation, G(50), plus snowmelt, G(51), exceed the soil surface infiltration capacity, B(2)·B(10), runoff occurs to X(2). This water transfer is done in F(2,2). However, overland flow on forested land is rare (Anderson et al. 1976). In addition, unless precipitation data is input hourly instead of the present daily data, there is little potential for overland flow in the model.

G(55) = litter compartment water transfer ($cm^3\ h^{-1}$)

G(55) = AMAX1((G(50) + G(51)−G(53)
−G(54))−(B(3)−X(3)), 0.0)

where

G(50) = precipitation,
G(51) = snowmelt,
G(53) = litter surface evaporation,
G(54) = surface runoff,
B(3) = water storage capacity of forest floor litter,
X(3) = current water content of forest floor litter.

This function does a mass balance of the forest floor litter storage, X(3), to determine the volume of water flow from X(3) into X(4). Inputs of precipitation, G(50), and snowmelt, G(51), are added; outputs of litter evaporation, G(53), and surface runoff, G(54), are subtracted. If X(3) is not at capacity, the deficit, B(3)-X(3), is first refilled, with the excess input water then cascading into X(4). The result equals F(3,4).

G(56) = root zone Soil A water transfer ($cm^3\ h^{-1}$)

$$G(56) = AMAX1(G(55)-(B(4)-X(4)),0.0)$$

where

G(55) = litter compartment water transfer,
B(4) = maximum water storage in root zone Soil A,
X(4) = current water storage in root zone Soil A.

As in G(55), a mass balance is done for X(4). Input from X(3) is added as G(55), water used to refill any deficit, B(4)-X(4), is subtracted, and the remainder cascaded to X(5). G(56) equals F(4,5).

G(57) = root zone Soil B water transfer ($cm^3\ h^{-1}$)

$$G(57) = AMAX1(G(56)-(B(5)-X(5)),0.0)$$

where

G(56) = root zone Soil A water transfer,
B(5) = maximum water storage in root zone Soil B,
X(5) = current water storage in root zone Soil B.

Again, input from X(4) is added until any deficit in X(5) is filled, B(5)-X(5). The excess water cascades into the subsurface outflow compartment, X(6), with an unlimited capacity. G(57) equals F(5,6).

Inherent in the mass balances of G(55), G(56), and G(57) are two assumptions. First, they do not allow soil supersaturation. All water in excess of field capacity is routed to the lower compartment. A second related assumption is that they effectively treat saturated hydraulic conductivity of the soil as infinite. At each hourly iteration, excess water is immediately routed to the lower compartment with no lag time. This was done to reduce the model requirements for soil physical data, and because these rather short-term phenomena were of small importance to seasonal water stress development. In some areas and for certain applications, this part of the model may require more sophisticated treatment.

G(58) = canopy evaporation ($cm^3\ h^{-1}$)

$$G(58) = Z(2)/4.\cdot B(10)-G(50)$$

where

Z(2)/4. = precipitation, entered from 0000 to 0400 hours,
B(10) = ground surface area,
G(50) = effective precipitation.

Water Withdrawal

G(60) = leaf water storage, current available (cm^3)

$$G(60) = B(8)\cdot(1.-G(10)/B(14)+B(13)/B(14))$$

where

B(8) = maximum available leaf storage,
G(10) = predawn leaf water potential, $B\psi_l$,
B(14) = leaf osmotic potential, stomatal closure threshold,
B(13) = spring minimum $B\psi_l$.

Recent research on the role of internal water storage in plant water relations (Hellkvist et al. 1974, Roberts 1977, Richter 1978, Waring and Running 1978, Waring et al. 1979, Running 1980c) has demonstrated that leaf water content and leaf water potential are directly related. This equation reduces available leaf water storage as predawn ψ_l increases, G(10), and approaches the leaf osmotic potential, B(14), where stomata close.

G(61) = leaf storage exchange rate ($cm^3\ h^{-1}$)

$$G(61) = X(8)/B(16)$$

where

X(8) = leaf water storage,
B(16) = leaf water depletion coefficient.

Although available leaf water storage has been studied in some detail, the short-term exchange rates of water from leaf tissue has not. The flow of water through leaf tissue greatly exceeds the diurnal net change in leaf water content. This function, taken from Running (1980c) on *Pinus contorta*, limits the hourly exchange rate of water from leaf storage, X(8), and is necessary for both biological and mathematical stability of leaf water exchange.

G(62) = stem water transport ($cm^3\ h^{-1}$)

$$G(62) = 0.0$$
$$IF(G(61)\ .GE.\ G(18))\ G(62) = AMAX1(G(60)-X(8),G(18)/B(16))$$
$$IF(G(61)\ .LT.\ G(18))\ G(62) = G(18)-G(61)$$

where

G(61) = leaf storage exchange rate,
G(18) = hourly stand transpiration,
G(60) = current leaf water storage,
X(8) = leaf water storage,
B(16) = leaf water depletion coefficient.

This function computes the water flow from X(7) to X(8) by determining how much of the transpiration demand can be satisfied by X(8), because in order to retain mass balance in the model, all transpiration demands must be met. When demand generates water stress by water depletion in various parts of the model, transpiration is reduced in future iterations by feedback controls on k_l. If exchangeable water in X(8), G(61), exceeds the transpiration demand G(18), then G(62) can either refill previous X(8) deficits G(60)-X(8) or a fraction of the demand G(18)/B(16). In the more normal case, where demand G(18) exceeds supply G(61), then G(62) requests flow from X(7) to cover all demand above exchangeable supply in X(8), G(18)-G(61). G(62) equals F(7,8).

G(66) = stem storage exchange rate ($cm^3\ h^{-1}$)

$$G(66) = X(7)/B(17)$$

where

X(7) = stem water storage,

B(17) = stem water exchange coefficient.

From research by Waring and Running (1978), Waring et al. (1979), and Running (1980c), there is data on three different coniferous species showing sapwood water depletion rates. This function limits the amount of water that can be withdrawn from X(7) on any one iteration by a rate constant B(17).

G(67) = root zone Soil A water uptake ($cm^3\ h^{-1}$)

$$G(67) = AMIN1(G(62)–G(66), (B(7)–X(7)/B(17), X(4)/B(17))$$

where

G(62) = stem water transport,

G(66) = stem storage exchange rate,

B(7) = maximum available stem water storage,

X(7) = current stem water storage,

B(17) = stem and soil water exchange coefficient,

X(4) = root zone Soil A soil water.

Flow from X(4) into X(7) is determined by the demand, G(62), minus any that can be satisfied by X(7), G(66). If there is no demand (i.e., at night), but X(7) is not full, flow will come into X(7) to fill this deficit, B(7)-X(7), subject to the B(17) exchange coefficient. The final control of F(4,7) uptake is that water withdrawal cannot exceed the exchangeable supply in rooting zone Soil A, X(4)/B(17). G(67) equals F(4,7).

G(68) = root zone Soil B water uptake ($cm^3\ h^{-1}$)

$$G(68) = AMIN1(G(62)–G(66)–G(67), (B(7)–X(7))/B(17))$$

where

G(62) = stem water transport,

G(66) = stem storage exchange rate,

G(67) = root zone Soil A water uptake,

B(7) = maximum available stem water storage,

X(7) = current stem water storage,

B(17) = stem water exchange coefficient.

Similar to G(67), G(68) is the water requirement needed to fulfill transpiration demand minus supply already contributed by stem water, G(66), and by X(4), G(67). This function chooses the minimum of two calculated flow potentials—the remaining demand or the exchangeable supply in X(7). If X(7) is not full, the deficit B(7)-X(7) can also be filled subject to the exchange coefficient limit B(17).

Water uptake is controlled by a feedback loop where soil moisture depletion, X(4) and X(5), increase predawn plant moisture stress, G(10), which reduces k_l, G(13), and transpiration, G(18), thus reducing water uptake demand, G(67) and G(68).

If transpiration demand exceeds supply in X(4), X(7), and X(5), which could only happen after months of progressive tree water stress and depletion of soil moisture to zero, X(5) would become negative. This means the tree or stand died of water stress!

G(69) = total root system water uptake ($cm^3\ h^{-1}$)

$$G(69) = G(67) + G(68)$$

where

G(67) = root zone Soil A water uptake,

G(68) = root zone Soil B water uptake,

Total root system uptake is combined for use in calculating diurnal leaf water potential in G(73).

Leaf Water Potential, Flow Resistances, Transpiration Ratios

G(70) = root resistance, soil temperature influences (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$IF(Z(5)\ .LE.\ 0.0)\ G(70) = 10.0$$
$$IF(Z(5)\ .GT.\ 0.0)\ G(70) = 1.0/Z(5)$$

where

Z(5) = soil temperature,

10.0 = a high soil resistance limit when soil temperature is less than 0° C; also protects the fraction from division by 0.0.

Recent studies have found root resistance to water uptake to increase rapidly as soil temperature approaches freezing (Babalola et al. 1968, Havranek 1972, Kaufmann 1975, Running and Reid 1980). These effects have been found in different conifer species and are partially physiological in nature. Increasing water viscosity explains only a part of the observed increase in flow resistance. The function in figure 8 approximates the data of Running and Reid (1980) on *Pinus contorta* and of Kaufmann (1975) on *Picea engelmannii.*

G(71) = flow resistance, soil water influences (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$G(71) = -0.28 + 2.0 \cdot G(10)$$

where

–0.28, 2.0 = empirical coefficients to fit data from Running (1980b),

G(10) = predawn leaf water potential.

The importance of flow resistance in the overall development of water potential gradients in coniferous trees has been quantified using a root excision technique (Roberts 1977, Running 1980b). Root resistance appears to increase as a direct function of decreasing soil water potential. This function increases flow resistance as predawn leaf water potential increases (negative ψ values are treated as positive numbers in the model, fig. 9). These data were from trees 3-5 m tall. Both the relaive and absolute influence of root resistance probably will be different on larger trees.

G(72) = total root resistance (MPa $\mu g^{-1}\ cm^{-2}\ s^{-1}$)

$$G(72) = G(70) + G(71)$$

where

G(70) = root resistance, soil temperature influences,

G(71) = root resistance, soil water influences.

G(73) = leaf water potential, ψ_l (MPa)

$$G(73) = AMIN1(G(10) + G(72) \cdot (G(69) \cdot 278.0/B(9)), B(14))$$

where

G(10) = predawn leaf water potential,
G(72) = total root resistance,
G(69) = total root water uptake,
278.0 = combines the constants $10^6 \mu g\ g^{-1}$ and $3{,}600\ s\ h^{-1}$,
B(9) = stand leaf area,
B(14) = leaf osmotic potential, stomatal closure threshold.

From plant water relations theory:

$$T = (\psi_{soil} - \psi_{leaf})/R_{total}$$

where

T = transpiration rate,
$\psi_{soil}-\psi_{leaf}$ = the soil to leaf water potential gradient,
R_{total} = the total resistance to water flow between the soil and leaf.

This equation can be rearranged to predict ψ_{leaf} as follows: $\psi_{leaf} = \psi_{soil} + R_{total} \cdot T$ (ψ treated as positive value) and has been used in a number of studies (Elfving et al. 1972, Kaufmann and Hall 1974, Hinckley et al. 1978). However, as pointed out by Waring and Running (1976, 1978) and Running (1980c), system capacitance confuses this equation. I have modified the equation by substituting G(10) for ψ_{soil} and by using G(69) instead of transpiration G(18) for water flux. This allows water to be withdrawn from internal reservoirs before ψ_l begins to increase and produces the diurnal ψ_l hysteresis typically found in trees (Jarvis 1975, Running 1980a). Using root water uptake, G(69), to generate ψ_l also agrees with studies showing the major component of overall flow resistance, and ψ gradient development to be at the soil-root interface (Robert 1977, Running 1980b).

Development of ψ_l is limited in this equation to B(14), the stomatal closure threshold, which typically varies between 1.5 and 2.3 MPa for temperate conifers (Hinckley et al. 1978). Under severe stress, trees can exceed this value, although the model cannot presently handle that circumstance.

G(76) = transpiration/potential transpiration ratio (dim.)

$$G(76) = G(16)/B(12)$$

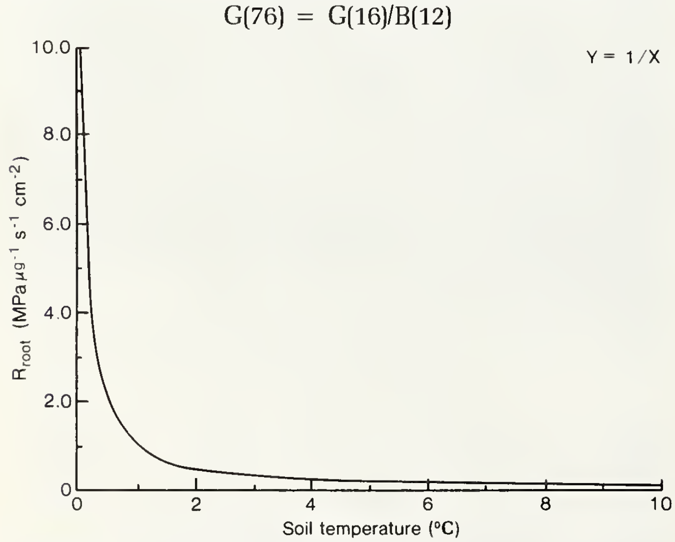

Figure 8.—Decreasing soil temperature produces a nonlinear increase in root water flow resistance.

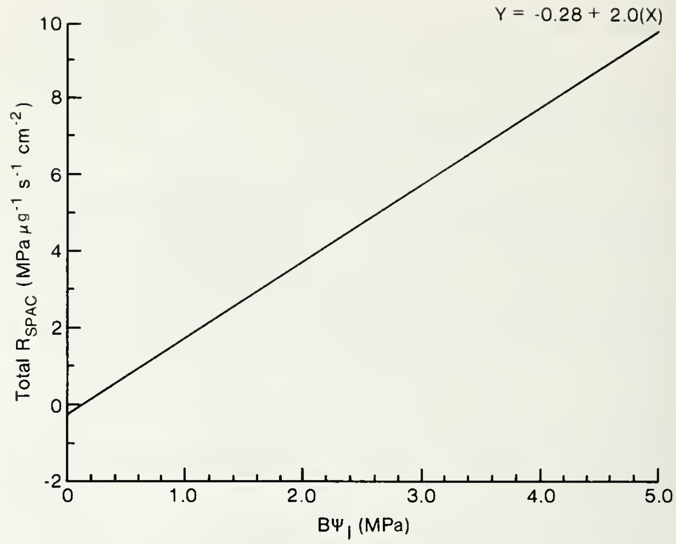

Figure 9.—As tree water stress, Bψ_l, increases, the total water flow resistance in the tree increases.

where

G(16) = k_l, canopy average,
B(12) = maximum average k_l.

The T/PT ratio provides a convenient quick measure of the current degree of stomatal closure controlling water loss (Reed and Waring 1974). This equation simplifies the T/PT ratio by removing the humidity deficit term from the numerator and denominator.

G(77) = areal transpiration (mm h^{-1})

$$G(77) = G(18)/B(10) \cdot 10$$

where

G(18) = stand transpiration,
B(10) = ground surface area,
10 = conversion factor from $cm^3\ h^{-1}$ to $mm\ h^{-1}$.

This calculates transpiration in simple water depth equivalence, as is routinely used in hydrology literature.

SPECIAL FUNCTIONS

Special Function S1—Frost k_l Function

```
   Function S1(TAIR, XHOUR, COND)
      IF(XHOUR – 5.0) 91, 90, 91
90 SRT = TAIR
91 IF(SRT . GT . 0.0) GO TO 92
   S1 = AMAX1(COND + 0.02 · SRT, 0.005)
   IF(SRT . LT . – 7.0) S1 = 0.005
   GO TO 93
92 S1 = COND + COND · 0.003 · (TAIR – 10.0)
93 RETURN
   END
```

The effect of air temperature on k_l is calculated in Function S1 and called by G(15). The temperature effect has two sections. When air temperature is above 10° C, k_l is increased modestly (0.003 cm s^{-1} °C^{-1}), if below 10° C, k_l is decreased by the same coefficient (Hinckley et al. 1978). There is evidence that subfreezing night temperatures retard stomatal opening even after temperature recovery (Neilson and Jarvis 1976, Fahey 1979,

Kaufmann 1982); therefore, the other part of Function S1 determines if frost occurred at dawn, defined as 0500 hours (SRT). If it had frozen, a much stronger k_l reduction is used (0.02 cm s^{-1} °C^{-1}) until 0500 the next morning.

Special Function S3—Absolute Humidity Deficit

```
Function S3 (TA, RH)
ESD  = 6.1078 · EXP((17.269 · TA)/(237.3 + TA))
ES   = RH/100 · ESD
VPD  = AMAX1((ESD – ES), 0.0)
S3   = 217.0 E –6 · VPD/(TA + 273.16)
RETURN
END
```

If the evaporating surface of a leaf is assumed to be at saturation and leaf temperature to equal air temperature, the evaporative demand in mass units can be obtained by first calculating saturation vapor pressure at TAIR using the equation of Murray (1967). Then calculate ambient vapor pressure (ES) using input relative humidity (RH). Vapor pressure deficit is defined as (ESD - ES). Absolute humidity deficity (ABSHD) in grams per cubic centimeter is then calculated from VPD and TA and returned to G(1) as S3. This function can be modified easily to calculate ABSHD from dewpoint or wetbulb depression instead of relative humidity.

DAYTRANS

The primary purpose of DAYTRANS is to develop a more simplified, less data-intensive model that retains as much of the prediction accuracy of H2OTRANS as possible. A major simplification was going to a daily timestep in DAYTRANS. As a result, computer execution cost is also greatly reduced. The overall structure and perspective of the models are similar. DAYTRANS was written after completion of H2OTRANS by removing the less critical sections of H2OTRANS. Because much of the documentation of DAYTRANS duplicates H2OTRANS, discussion here will concentrate on the differences between the models. Readers can refer to the comprehensive H2OTRANS section for documentation of the sections that are basically identical. See figure 2 for the DAYTRANS compartment flow diagram.

STATE VARIABLES—X(i)

A list of state variables follows. See definitions for the comparable state variables in the H2OTRANS section.

		Unit
X(1) =	snowpack water content	cm^3
X(2) =	root zone soil water content	cm^3
X(3) =	tree sapwood water content	cm^3
X(4) =	transpiration (unlimited capacity)	cm^3
X(5) =	surface runoff (unlimited capacity)	cm^3
X(6) =	subsurface outflow (unlimited capacity)	cm^3
X(7) =	evaporation (unlimited capacity)	cm^3

FLOW FUNCTIONS—F(i,j)

A list of flow functions follows. See F(i,j) section in H2OTRANS for explanations.

F(1,2) = snowmelt input, G(50)
F(2,2) = precipitation input, G(1)
F(2,3) = root water uptake, G(53)
F(2,5) = surface runoff, G(51)
F(2,6) = subsurface outflow, G(52)
F(3,4) = transpiration, G(19)
F(7,7) = evaporation, canopy and litter, G(9)

DRIVING VARIABLES—Z(i)

DAYTRANS uses the following driving variables.

		Unit
Z(1) =	Julian date	day
Z(2) =	precipitation	cm
Z(3) =	air temperature (daylight average)	°C
Z(4) =	absolute humidity deficit (daylight average)	g cm^{-3}
Z(5) =	soil temperature, 20 cm	°C
Z(6) =	incoming shortwave radiation (daylight average)	ly min^{-1}
Z(7) =	daylength (sunrise-sunset)	s
Z(8) =	night minimum air temperature	°C

A primary reason for using DAYTRANS occurs when only daily meteorological data is available. It became evident executing both models that a critical factor in the success of the DAYTRANS simulation was the accuracy with which the climatic variables were averaged. As more meteorological stations record on microprocessor data-loggers, daily averages can be generated by electronic integration of the variable inputs throughout the day. Some suggestions on averaging certain daily meteorological data for use in DAYTRANS are presented next. Note that Z(3), Z(4), and Z(6) must be averaged for the daylight period only. This is based on the assumption that transpiration and water stress development occur only during the day.

Air Temperature—Z(3)

Frequently, only maximum and minimum air temperatures are recorded for a day. If the daylight course of air temperature is assumed to approximate three quadrants of a sine function (Parton and Logan 1981) as shown in figure 10, a simple approximation of daylight average air temperature can be derived.
The arithmetic mean is:

$$\bar{T} = (T_{max} + T_{min})/2 = \sin 0.$$

But integrating the sine function yields

$$\frac{1}{PI - (-PI/2)} \int_{-PI/2}^{PI} \sin \times dx = 0.212$$

where
PI = 3.1416.

So

$$T_{ave} = 0.212(T_{max} - \bar{T}) + \bar{T}$$

where

T_{ave} = average daylight air temperature,
$\bar{T}$ = arithmetic mean of T_{max} and T_{min}.

This equation was used to generate a DAYTRANS data file that was compared against a data file developed from averaging recorded hourly air temperature values. The regression of hourly averaged air temperature daylight averages against the sine function weighted daylight averages was:

$$T_{ha} = -1.14 + 1.12\ T_{sf} \quad R^2 = 0.93\ n = 120\ \text{days}$$

where

T_{ha} = air temperature, hourly averaged,
T_{sf} = air temperature, weighted sine function.

The same regression against arithmetic maximum-minimum averages was

$$T_{ha} = 0.74 + 1.20\ T_{mm} \quad R^2 = 0.88\ n = 120\ \text{days}$$

where

T_{mm} = maximum-minimum averaged temperatures.

The sine function-weighted average more closely approaches the optimum $T_{ave} = T_{ha}$ prediction, as shown by a comparison of Y-intercepts, slopes and correlation coefficients.

It should be emphasized that these data manipulations are done in developing the DAYTRANS input data file. This is not done internally by the DAYTRANS program, although it could be if a permanent data base required it.

Absolute Humidity Deficit—Z(4)

Absolute humidity deficit is calculated for Z(4) by reading in TAIR, air temperature, and XRHUM (relative humidity). Four equations are then used to calculate saturation vapor pressure, absolute humidity, and absolute humidity deficit. These equations are covered in Special Function S3 in H2OTRANS. Some considerations for estimating daily average relative humidity follow.

The diurnal course of relative humidity often is a mirror image of the air temperature trace because of the influence of air temperature on saturation vapor pressure. Consequently, a sine function-weighted correction was also done for humidity daily averages. The analysis was similar to that in figure 10, except that the Y-axis was reversed.

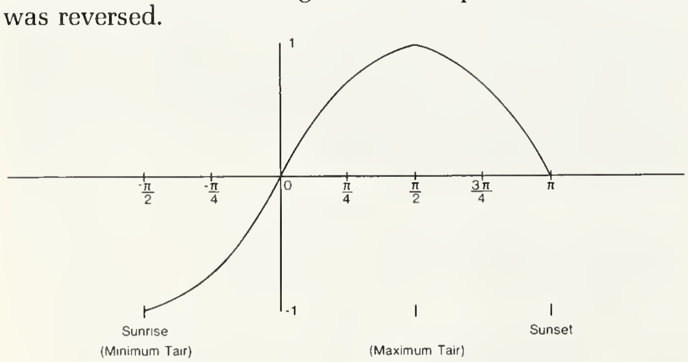

Figure 10.—A diagram analyzing the use of a sine function to approximate average air temperature and relative humidity during daylight hours, given only maximum and minimum values.

$$RH_{ave} = \bar{\bar{RH}} - 0.212\ (\bar{\bar{RH}} - RH_{min}).$$

The regression between hourly averaged RH and the sine function-weighted daily RH was

$$RH_{ave} = -17.0 + 1.32\ RH_{sf} \quad R^2 = 0.84\ n = 120\ \text{days}$$

This corrected RH was also an improvement over a daily RH produced merely by averaging the maximum and minimum RH.

Again, it should be stated that these data reductions must be done outside of the main DAYTRANS program. Also, this sine function approximated diurnal humidity curve would not be appropriate when using an absolute measure of atmospheric water vapor such as dewpoint.

Soil Temperature—Z(5)

Because the diurnal temperature variation at 20-cm depth is usually less than 1° C, any midday soil temperature measurement is an adequate daily average for the purposes of this model.

Incoming Shortwave Radiation—Z(6)

If total daily radiation is collected, radiation divided by day length in minutes will provide the daily average used in Z(6). Day length for a flat surface is computed in Z(7).

In the absence of any radiation data, daily potential radiation can be determined (Garnier and Ohmura 1968, Swift 1976). Assuming a sine wave approximation of a cloudless diurnal radiation trace, peak daily radiation times 0.7 provides a fair approximation of daily average incoming radiation for relatively clear areas.

Day Length—Z(7)

```
XD    = JD - 79
IF(XD . LT . 0.0) XD = 286.0 + JD
DAY   = 3.125·(SIN(XD·0.01721)) + 12.0
Z(7)  = DAY · 3600 · 0.8
```

This sine function, driven by Julian date (JD), computes day length in hours (DAY), at 41° N. latitude, for a flat surface, on any day of the year. Because this day length calculation overestimates the duration of daylight with sufficient intensity to open stomata (0.1 ly min^{-1}), analysis of diurnal radiation traces showed that a 0.8 correction more closely approximates the length of effective daylight for transpiration. The sine equation can be adjusted for any latitude by the 3.125 coefficient (3.5 for 45° N.) and is typically accurate to within 15 minutes per day. More complex equations correcting for different slopes and aspects are also available (Garnier and Ohmura 1968, Swift 1976).

AUXILIARY CONSTANTS—B(i)

		Unit
B(1)	= maximum soil surface infiltration rate	cm day^{-1}
B(2)	= root zone soil capacity	cm^3
B(3)	= tree sapwood storage capacity	cm^3

B(4)	=	tree or stand leaf area	cm^2
B(5)	=	maximum canopy leaf conductance, k_l	$cm\ s^{-1}$
B(6)	=	canopy and litter interception coefficient	cm
B(7)	=	ground surface area	cm^2
B(8)	=	snowmelt coefficient	$cm\ °C^{-1}$
B(9)	=	midcrown tree height	m
B(10)	=	spring minimum predawn ψ_l	MPa
B(11)	=	stomatal closure threshold	MPa

INTERMEDIATE VARIABLES—G(i)

G(1) = effective precipitation ($cm^3\ day^{-1}$)

G(1) = AMAX1((Z(2)–(B(4)/B(7)) · B(6)) · B(7), 0.0)

where
Z(2) = precipitation,
B(4) = stand leaf area,
B(6) = canopy and litter interception coefficient,
B(7) = ground surface area.

This equation reads input precipitation, Z(2), subtracts canopy and litter interception, B(6), as a function of leaf area index, B(4)/B(7), and multiplies by ground surface area, B(7), to give volume of water input. See G(50) in H2OTRANS.

G(2) = available water fraction, root zone ($cm^3\ cm^{-3}$)

G(2) = X(2)/B(2)

where
X(2) = current root zone water storage,
B(2) = root zone water capacity.

G(3) = available water fraction, sapwood ($cm^3\ cm^{-3}$)

G(3) = X(3)/B(3)

where
X(3) = current sapwood water storage,
B(3) = sapwood storage capacity.

G(4) = snowmelt ($cm^3\ day^{-1}$)

G(4) = AMAX1(B(8)·Z(3)·B(7), 0.0)
IF (X(1) .LE. 0.0) G(4) = 0.0

where
B(8) = snowmelt coefficient,
Z(3) = air temperature,
B(7) = ground surface area,
X(1) = current snowpack water content.

This equation melts the snowpack, X(1) at a rate B(8), based on average day air temperature, Z(3), multiplied by ground surface area, B(7), and gives the volume of water melted. See G(51) in H2OTRANS.

G(5) = leaf area index ($cm^2\ cm^{-2}$)

G(5) = B(4)/B(7)

where
B(4) = stand leaf area,
B(7) = ground surface area.

G(9) = canopy and litter evaporation ($cm^3\ day^{-1}$)

G(9) = Z(2)·B(7)–G(1)

where
Z(2) = precipitation,
B(7) = ground surface area,
G(1) = effective precipitation into the soil.

Evaporation of water from canopy and litter interception is calculated by G(9).

G(10) = predawn leaf water potential, Bψ_l (–MPa)

G(10) = AMAX1(B(10), 0.2/G(2) + 0.01·B(9), 0.0)

where
B(10) = spring minimum predawn ψ_l,
0.2 = curve-fitting coefficient,
G(2) = available water fraction, root zone,
0.01 = hydrostatic gradient constant ($MPa\ m^{-1}$),
B(9) = midcrown tree height.

Pre-dawn leaf water potential is predicted from available soil moisture G(2), and is corrected for tree height. See G(10) in H2OTRANS.

G(12) = light-saturated leaf area index ($m^2\ m^{-2}$)

G(12) = 10.0·(1.0–EXP(–4.6·Z(6)))

where
10.0, 1.0, –4.6 = curve-fitting coefficients,
Z(6) = incoming shortwave radiation.

This equation computes the amount of leaf area index that would be receiving at least 10% of full sunlight at the measured radiation intensity, Z(6), and assumed vertical attenuation. See G(11) in H2OTRANS.

G(13) = radiation-induced k_l limiting fraction (dim.)

G(13) = 1.0–((G(5)–G(12))/G(5))
IF(G(12) .GT. G(5)) G(13) = 1.0

where
G(5) = leaf area index,
G(12) = light-saturated leaf area index.

Canopy leaf conductance is reduced by G(13), the fraction of the canopy receiving insufficient radiation to open stomata. See G(12) in H2OTRANS.

G(14) = k_l, predawn leaf water potential correction ($cm\ s^{-1}$)

G(14) = B(5) – (B(5)/B(11)–B(10))·(G(10)–B(10))
IF(G(10) .GE. B(11)) G(14) = 0.005

where
B(5) = maximum canopy k_l,
B(5)/B(11)–B(10) = the slope of the k_l reduction calculated by the range of k_l (maximum (B(5)) to 0) divided by the corresponding range of ψ_l (spring minimum ψ_l, B(10) to stomatal closure point, B(11)).
G(10) = predawn leaf water potential,
B(10) = spring minimum ψ_l,
0.005 = minimum k_l, stomatal closure.

This important function relates reduction in canopy k_l to soil moisture deficits through the predawn leaf water potential function, G(10). See the discussion in H2OTRANS for G(13).

G(15) = k_l, humidity correction (cm s^{-1})

G(15) = G(14)–(G(14)·0.05·(Z(4)·10^6–4.0))
IF(G(15) .LE. 0.0) G(15) = 0.005

where
G(14) = k_l, leaf water potential effects,
0.05 = slope of k_l reduction,
Z(4) = absolute humidity deficit,
10^6 = unit scalar,
4.0 = humidity control threshold factor,
0.005 = stomatal closure constant.

This function produces the humidity effects on k_l analagous to G(14) in H2OTRANS.

G(16) = k_l, air temperature correction (cm s^{-1})

G(16) = G(15) + G(15)·0.003·(Z(3)–10.0)
IF(Z(8) .LT. 0.0) G(16) = AMAX1(G(15) +0.02·Z(8), 0.005)

where
G(15) = k_l, humidity effects,
0.02, 0.003 = slope of k_l reduction (cm s^{-1} °C^{-1}),
Z(3) = air temperature,
10.0 = temperature reduction threshold,
Z(8) = night minimum air temperature,
0.005 = k_l at stomatal closure.

These equations increase k_l slightly with air temperatures above 10° C, reduce k_l at temperatures between 0° and 10°, and markedly reduce k_l at night minimum temperatures below 0.0°. See special function S1, H2OTRANS.

G(17) = k_l, final canopy average (cm s^{-1})

G(17) = G(16)·G(13)

where
G(16) = k_l, plus humidity, air temperature and leaf water potential controls,
G(13) = k_l, radiation reduction fraction,
See G(17) in H2OTRANS.

G(18) = transpiration flux density (g cm^{-2} s^{-1})

G(18) = Z(4)·G(17)

where
Z(4) = absolute humidity deficit,
G(17) = k_l, final canopy average,
See G(17) in H2OTRANS.

G(19) = daily stand transpiration (g day^{-1})

G(19) = G(18)·B(4)·Z(7)

where
G(18) = transpiration flux density,
B(4) = stand leaf area,
Z(7) = day length,
Final stand transpiration G(19) = F(3,4).

G(20) = transpiration/potential transpiration ratio (dim.)

G(20 = G(17)/B(5)

where
G(17) = k_l, final canopy average,
B(5) = maximum k_l,
See G(76) in H2OTRANS.

G(21) = areal transpiration (mm day^{-1})

G(21) = G(19)/B(7)·10.0

where
G(19) = daily stand transpiration,
B(7) = ground surface area.

G(50) = precipitation and snowmelt water input (cm^3 day^{-1})

G(50) = G(4)
IF (X(1)–G(4) .LT. 0.0) G(50) = X(1)

where
G(4) = snowmelt,
X(1) = snowpack water content.

Water input into X(2) comes from precipitation and snowmelt. Snowmelt, G(4), cannot exceed the current snowpack water content, X(1). G(50) equals F(1,2).

G(51) = surface runoff (cm^3 day^{-1})

G(51) = 0.0
IF ((G(1)+G(4))/B(7) .GT. B(1)) G(51) = (G(50)–B(1))·B(7)

where
G(1) = precipitation,
G(4) = snowmelt,
B(7) = ground surface area,
B(1) = maximum soil surface infiltration rate,
G(50) = precipitation and snowmelt water input.

Water input in excess of the maximum soil surface infiltration rate is routed to surface runoff. G(51) equals F(2,5).

G(52) = subsurface outflow (cm^3 day^{-1})

G(52) = 0.0
IF (X(2)+G(50) .GT. B(2)) G(52) = X(2)+G(50)–G(51)–B(2)

where
X(2) = current root zone soil water content
G(50) = precipitation and snowmelt water input,
G(51) = surface runoff,
B(2) = root zone soil water capacity.

If water input, G(50), minus surface runoff exceeds the capacity of X(2), the excess water goes to subsurface outflow. G(52) equals F(2,6).

G(53) = root water uptake (cm^3 day^{-1})

G(53) = B(3)–X(3)+G(19)

where
B(3) = tree sapwood storage capacity,
X(3) = current sapwood water storage,
G(19) = daily transpiration.

This equation computes water transfer from X(2) to X(3) based solely on deficits in X(3) and transpiration demand. In a previous model version, I had a soil-water uptake resistance also controlling water movement at this point, but it seems to be unnecessary.

The feedback resistance produced by the effects of soil water deficit on predawn leaf water potential, G(10), leaf conductance, G(13), and transpiration, G(19), controls the overwithdrawal of water from X(2) except

after extreme, extended water stress. At that point the model should predict tree mortality!

Two additional capabilities were recently added to DAYTRANS, although they were not included in the results section.

1. Penman-Monteith calculation of transpiration

```
      FUNCTION PENMON(TAIR,RAD,VPD,XLAI,COND)
      GAMMA=0.646+0.0006*TAIR
      PLAI=XLAI/2.
      T1=TAIR+0.5
      T2=TAIR-0.5
      SVP1=6.1078*EXP((17.269*T1)/(237.0+T1))
      SVP2=6.1078*EXP((17.269*T2)/(237.0+T2))
      SLOPE=SVP1-SVP2
      XNETR=RAD*0.8*697.3
      CP=1.01E+3
      PA=1.292-0.00428*TAIR
      RA=5.0
      RS=100./COND
      XLAT=(2.501 - 0.0024*TAIR) * 1.0E+6
      XTRANS=((SLOPE*XNETR)/PLAI
    C+(CP*PA)*(VPD/RA))/
  C  (SLOPE+GAMMA*(1.0+RS/RA))
      PENMON=XTRANS/(XLAT * 10.)
      RETURN
      END
```

This is an adaptation of the widely used Penman-Monteith equation (Jarvis et al. 1976):

$$\lambda E = \frac{(\Delta R\eta/PLAI) + C_p P(VPD)/r_a}{\Delta + \gamma (1 + r_s/r_a)}$$

where

λ	=	XLAT = latent heat of vaporization of water (J kg^{-1}),
E	=	XTRANS = evaporation (W m^{-2}),
PENMON	=	evaporation (g cm^{-2} s^{-1}),
Δ	=	SLOPE = slope of the saturation vapor pressure curve at T_{air}, (mbar °C^{-1}),
$R\eta$	=	XNETR = net radiation (W m^{-2}),
PLAI	=	projected leaf area index,
C_p	=	CP = specific heat of air (J kg^{-1} °C^{-1}),
P	=	PA = density of air (Kg m^{-3}),
VPD	=	vapor pressure deficit (mb),
r_a	=	RA = aerodynamic resistance (s m^{-1}),
γ	=	GAMMA = psychrometric constant (mb °C^{-1}), calculated by $\gamma = C_pP/\lambda$,
r_s	=	RS = stomatal resistance, calculated as $1/k_l$ G(17), (s m^{-1})).

Under conditions of high net radiation but low air temperature common in spring, radiant energy becomes a significant driving variable for evaporation. This equation assumes a constant r_a of 5.0 s m^{-1} with no windspeed input. It also divides the net radiation term by projected leaf area index to more realistically express the radiant energy loading on different canopy layers. This calculation of stand transpiration can be substituted for G(17) in H2OTRANS or G(18) in DAYTRANS.

2. Net photosynthesis subroutine

```
      SUBROUTINE PHOTO
      COMMON K,X(2,20),F(20,20),G(100),
      B(100),Z(20),Y(160)
C
C     Z(10) = CANOPY AVERAGE RADIATION
C
      Z(10)=(Z(6)+Z(6)*EXP(-0.7*G(5)/2.))/2.
C
C     Z(9) = AVERAGE NIGHT TEMPERATURE
C
      Z(9)=(Z(3) + Z(8))/2.
C
      G(64)=((Z(10)-0.0143)/(Z(10)+0.322))*
C     (0.0182+0.0105*Z(3)-0.000194*(Z(3)**2))
      IF(G(64).LT.0.)G(64)=0.
      G(65)=(0.0006*(G(17)/1.6)*G(64))/
C     ((G(17)/1.6)+G(64))
      G(62)=0.001*(24.-Z(7)/3600.)*EXP(0.2*Z(9))
      G(66)=G(65)*Z(7)
      G(67)=G(66)-G(62)
      RETURN
      END
```

This subroutine was derived from the photosynthesis model of Lohammar et al. (1980).

G(65) = PSN = gross photosynthesis (mg cm^{-2} s^{-1})

$$G(65) = PSN = \frac{\Delta CO_2 (k_l \cdot g_m)}{k_l + g_m}$$

where

ΔCO_2	=	CO_2 gradient from the atmosphere to the carboxylation site in the leaf (≅0), taken as 0.0006 kg m^{-3}
k_l	=	G(17) = leaf conductance to water vapor (cm s^{-1}),
1.6	=	ratio of the diffusion coefficients of water vapor and CO_2 in the air,
g_m	=	G(64) = mesophyll CO_2 conductance (cm s^{-1}).

G(64) is calculated by Lohammar et al. (1980) as:

$$G(64) = g_m = \frac{I - I_o}{I + I_{1/2}} \cdot \alpha f(T)$$

where

I	=	Z(10) = incoming shortwave radiation (W m^{-2}) with a conversion factor of 1 W m^{-2} = 1.43 × 10^{-3} cal $cm^{-2}min^{-1}$,
I_o	=	light compensation point, where net PSN = 0, given as 10 W m^{-2} = 0.0143 cal cm^{-2} min^{-1},
$I_{1/2}$	=	the irradiance at which g_m is half of its maximum value, given as 225 W m^{-2} = –0.322 cal cm^{-2} min^{-1},
α f(T)	=	the maximum g_m at any air temperature T, generated by the polynomial equation:

$$\alpha = 0.0182 + 0.0105 (Z(3)) + 0.000194 (Z(3)^2)$$

This curve was fitted to data from Nielson and Jarvis (1976), R^2 = 0.67, and checked against a variety of other sources for conifers. It calculates a maximum g_m = 0.16 cm s^{-1} at 26.3° C.

G(66) = Daily net CO_2 uptake (mg cm^{-2})

$$G(66) = G(65) \cdot Z(7)$$

where

G(65) = gross photosynthesis (mg cm^{-2} s^{-1}),

Z(7) = daylength (s).

G(62) = Night foliar respiration loss (mg cm^{-2}

$$G(62) = 0.001 \cdot (24 - (Z(7)/3600)) \cdot \exp(0.2 \cdot Z(9))$$

where

24 – (Z(7)/3600) = night length (h),

Z(9) = average night air temperature (°C).

This equation was used by Emmingham and Waring (1977).

Finally, 24-hour net photosynthesis is approximated by

G(67) = 24-hour net CO_2 uptake (mg cm^{-2})

$$G(67) = G(66) - G(62)$$

where

G(66) = daily net CO_2 uptake,

G(62) = night foliar respiration loss.

RESULTS

This preliminary validation had two objectives. First was to test if H2OTRANS and DAYTRANS were capable of simulating the diurnal and seasonal patterns of transpiration and water stress development in lodgepole pine. Because transpiration of a stand cannot be measured directly, validation focused on diurnal and seasonal patterns of measurable variables ψ_l and k_l in individual trees and soil moisture depletion. The second objective was to determine if the much smaller, simplified DAYTRANS model could predict seasonal patterns with minimal resolution loss compared to H2OTRANS. The H2OTRANS model was designed as a research tool and requires more detailed climatic data and specialized parameter estimates. DAYTRANS was an attempt to scale the logic of the H2OTRANS model down to a level where input data requirements would be feasible for operational use.

FIELD VALIDATION SITE

During the fall of 1977, a study site was established at the USDA Forest Service Fraser Experimental Forest in the central Colorado Rocky Mountains. The site studied supported an uneven-aged *Pinus contorta* stand, with occasional *Populus tremuloides*, ranging in age from 10 years to the 12-m tall canopy dominants at 60 years. The elevation was 2,700 m, and topography level on a glacial outwash. Stand density was 2,740 trees per hectare with a basal area of 30.7 m^2 ha^{-1} and site index of 22.6 m at 100 years.

The climate of this area is cool and dry for coniferous forests. Temperature extremes of from –40° C to 32° C have been recorded. Frost is possible on any night during the growing season. Minimum temperatures on site during the summer of 1978 were always below 4° C, and maximum daily air temperatures averaged from 20° C to 23° C, with a high of 26° C. Midday relative humidity typically ranged from 15% to 25%, except during thunderstorms. Precipitation averages 58.4 cm per year, with nearly two-thirds falling as snow between October and May (Alexander and Watkins 1977).

Beginning on Julian date 130 (May 10), 1978, continuous meteorological data was recorded until JD 250 (September 10), 1978. Air temperature measured by a thermistor was continuously recorded by strip chart. Dewpoint temperature was measured with a heated lithium chloride dew point sensor, also recorded continuously on the strip chart. These instruments were mounted in a standard, vented weather station box placed 1.5 m above the ground. Onsite soil temperature at 15-cm depth was taken with a dial temperature probe once a day. Also, a sling psychrometer was used every two hours during daylight hours to take wet- and dry-bulb temperatures for backup measurement of air temperature and humidity. Precipitation and a continuous trace of incoming shortwave radiation were being recorded 5 km away at the Fraser Experimental Forest headquarters. At the end of the summer, these data were compiled into the format required for input into H2OTRANS and DAYTRANS as Z, or driving, variables.

PARAMETER ESTIMATES

To run the models, a number of site and stand parameters were also needed. Because a complete biomass survey of the stand could not be done and validation was focusing on individual tree responses, a single tree representative of the stand was defined for modeling. The characteristics of this tree follow:

Ground surface area = 3.5 m^2
Diameter (b.h.) = 8.2 cm
Height = 7.0 m
Needle weight = 2.87 kg
Needle area = 2.1×10^5 cm^2
LAI = 6.0
Sapwood basal area = 73.9 cm^2
Sapwood volume = 21,000 cm^3.

Trees of this general size had been used to gather data for some of the physiological responses in the model. Consequently, these parameter estimates can be verified from measured biomass data (Running 1980c). Also, the "observed" field data used in this preliminary validation were taken on trees of this size.

A list of initial conditions for the X(i), state variables, at the beginning of the H2OTRANS and DAYTRANS model runs on JD 130, 1978, and the B(i), constant parameters, is given in table 1.

VALIDATION RUNS

Simulation runs were made for JD 130 to 245, 1978, by H2OTRANS and DAYTRANS. The overall water budgets predicted by the two models were:

	H2OTRANS	DAYTRANS
Transpiration	36%	38%
Evaporation	15%	17%
Subsurface outflow	49%	45%
Total	42.9 cm	

This was taken from a total water supply during the period consisting of snowpack, soil water, and precipitation. Figure 11 plots the seasonal progression of transpiration and soil moisture depletion simulated by the models, and the actual soil moisture depletion measured on site by technicians using a neutron probe. The neutron probe data, taken at monthly intervals, from 0 to 1.5 m depth, at 15-cm increments, from four access tubes, is shown in Running (1980a). The initiation of soil moisture depletion and final magnitude of drawdown were predicted fairly accurately by both models. The models appear to overestimate water depletion rates somewhat during midsummer; however, the slope of overall seasonal depletion was fairly closely represented. DAYTRANS predicted transpiration rates roughly 5% higher than H2OTRANS during midsummer beginning around JD 170. This discrepancy is attributed to the difficulties of averaging evaporative demand accurately for the day and scaling the humidity reduction of k_l correctly in DAYTRANS to averaged values. Final seasonal transpiration estimates agree to within 4%, which is remarkable considering the much reduced resolution of DAYTRANS.

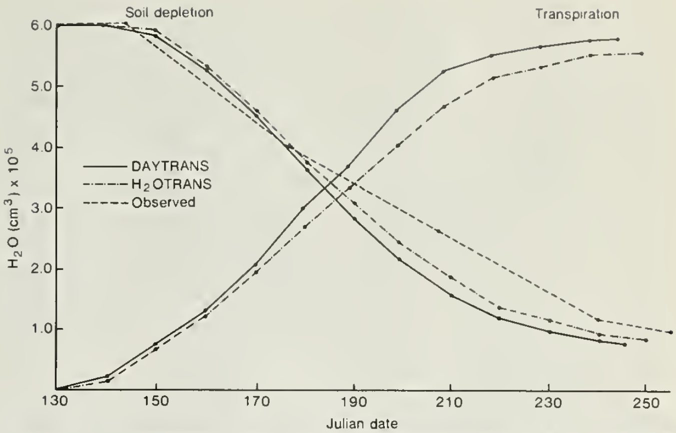

Figure 11.—Simulation runs comparing H2OTRANS and DAYTRANS results to observed data on lodgepole pine at the Fraser Experimental Forest study site during the summer of 1978. Soil water depletion was measured by a neutron probe. There is no observed data for transpiration; therefore, only the comparison of model predictions is shown.

Predawn leaf water potential, $B\psi_l$, is considered by many tree physiologists to be the best and most easily measured way of assessing seasonal water stress development in a tree. In figure 12, the H2OTRANS and DAYTRANS predictions of seasonal stress development $B\psi_l$ are shown compared to a compilation of observed $B\psi_l$ measurements taken at different lodgepole pine trees at the Fraser site throughout the summer of 1978. Again, both models performed well relative to each other and the measured field data.

Table 1.—Model conditions for the preliminary validation exercise

H2OTRANS			DAYTRANS		
X(i): Initial conditions (cm^3)			X(i): Initial conditions (cm^3)		
X(1)	= 7.2×10^5		X(1)	= 7.2×10^5	
X(2)	= 0.0		X(2)	= 6.0×10^5	
X(3)	= 1.0×10^4		X(3)	= 1.33×10^4	
X(4)	= 3.0×10^5		X(4)	= 0.0	
X(5)	= 3.0×10^5		X(5)	= 0.0	
X(6)	= 0.0		X(6)	= 0.0	
X(7)	= 1.6×10^3		X(7)	= 0.0	
X(8)	= 0.9×10^2				
X(9)	= 0.0				
X(10)	= 0.0				
B(i) Constant parameters			B(i): Constant parameters		
B(1)	= 0.015	cm h^{-1} °C^{-1}	B(1)	= 5.0×10^1	cm day^{-1}
B(2)	= 10.0	cm h^{-1}	B(2)	= 6.0×10^5	cm^3
B(3)	= 3.5×10^4	cm^3	B(3)	= 1.33×10^4	cm^3
B(4)	= 3.0×10^5	cm^3	B(4)	= 2.1×10^5	cm^2
B(5)	= 3.0×10^5	cm^3	B(5)	= 0.15	cm s^{-1}
B(6)	= 0.010	cm LAI^{-1} h^{-1}	B(6)	= 0.30	cm LAI^{-1}
B(7)	= 1.6×10^4	cm^3	B(7)	= 3.5×10^4	cm^2
B(8)	= 9.0×10^2	cm^3	B(8)	= 0.15	cm °C^{-1}
B(9)	= 2.1×10^5	cm^2	B(9)	= 7.0	m
B(10)	= 3.5×10^4	cm^2	B(10)	= 0.4	MPa
B(11)	= 7.0	m	B(11)	= 1.5	MPa
B(12)	= 0.15	cm s^{-1}			
B(13)	= 0.4	MPa			
B(14)	= 1.5	MPa			
B(15)	= 74.0	cm^2			
B(16)	= 2.0	h^{-1}			
B(17)	= 20.0	h^{-1}			

Leaf conductance is the most easily measured physiological variable that is closely related to transpiration. To evaluate the model's predictions of k_l, the seasonal progression of maximum daily k_l was plotted in figure 13 and compared to observed k_l data compiled from measurements on different lodgepole pine taken throughout the summer of 1978. The beginning of stress development around JD 185 is evident in figure 12, with corresponding reducing of k_l in figure 13. Note that in both figures 12 and 13 the models are relatively successful in predicting (1) the time of initial stress development, and (2) the overall rate of increase in stress (fig. 12) and reduction in k_l (fig. 13).

To further examine the ability of H2OTRANS to simulate diurnal dynamics of ψ_l and k_l, 19 days of ψ_l and k_l data from 12 different trees at the Fraser site were compiled. Each data point, representing a specific date and time of day, was plotted against the corresponding H2OTRANS simulated value for that date and time. The results of this analysis, shown in figure 14 for ψ_l and figure 15 for k_l, cover an extensive array of conditions of temperature, humidity, radiation, and soil moisture expected in measurements taken from sunrise to sunset throughout the summer. Both the slope and Y-intercept of the linear regression equation in figure 14 correspond well with the optimal 1:1 where every measured value is predicted exactly. It is evident in analyzing the scatter of points that the model tends to underestimate ψ_l in the 1.0-1.3 MPa range and overestimate ψ_l in the 1.3-1.5 MPa range.

The diurnal prediction of k_l was less successful, possibly because of the large number of factors controlling k_l. The Y-intercept of the regression line shows that at low k_l values (below 0.06 cm s^{-1}) H2OTRANS often overestimates k_l. At k_l values above 0.08 cm s^{-1} the model underestimates k_l. This illustrates the concept that when average "conservative" response equations are used in a model, the deviations from the average will be most noticeable at the extremes of the response curves. Fortunately, these high resolution errors compensated each other, allowing reasonable estimates of the longer term seasonal trends of tree water use and stress development.

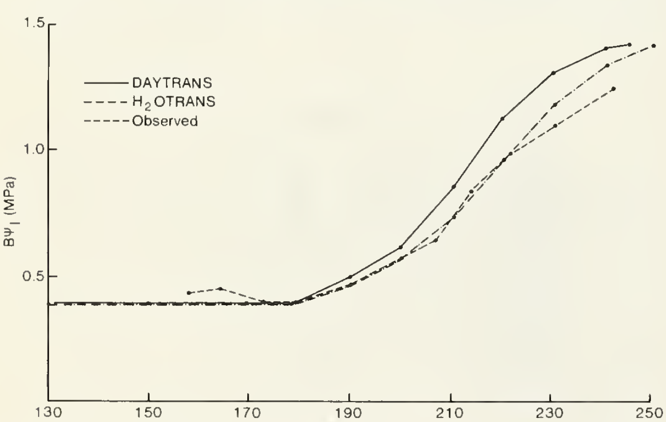

Figure 12.—A comparison of H2OTRANS and DAYTRANS predictions of increase in tree water stress (predawn leaf water potential, $B\psi_l$) with measured values on lodgepole pine at the Fraser Experimental Forest study site during the summer of 1978.

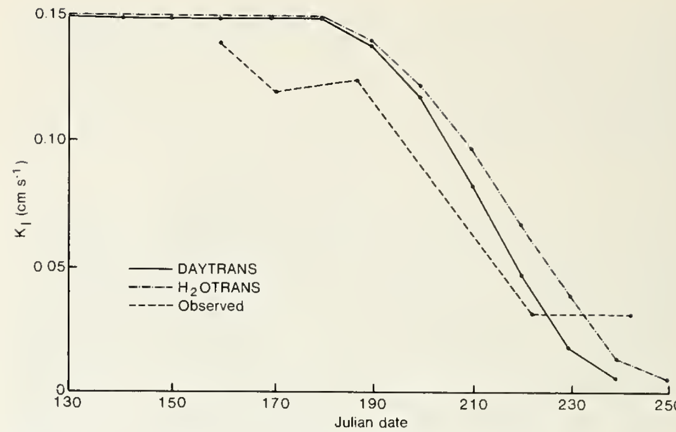

Figure 13.—Predicted and observed levels of maximum daily leaf conductance, k_l, on lodgepole pine at the Fraser site throughout the summer of 1978. Observed points represent an average of 9-11 diffusion porometer measurements taken throughout the tree crown.

SENSITIVITY ANALYSIS

To assess the response of the overall model to various "perturbations," a sensitivity analysis was run on DAYTRANS. A similar test was not run on H2OTRANS because the models are so similar and the cost and computer time of running the larger model was prohibitive. To execute this analysis, six independent variables were individually changed; first an increase of 50%, then a decrease of 50%, for a total of 12 model runs. The variables changed were initial snowpack water, X(1), rooting zone water capacity, B(2), leaf area, B(4), maximum k_l, B(5), interception coefficient, B(6), and snowmelt coefficient, B(8). Three dependent variables were analyzed to determine changes brought about by these +/-50% perturbations. The dependent variables were total transpiration, X(4), total subsurface outflow, X(6), and predawn leaf water potential, G(10). The results of this sensitivity test are given in table 2.

Changes in the snowpack primarily caused changes in subsurface outflow. Snowmelt goes through the system relatively quickly in the spring; therefore, once the rooting zone soil is saturated, the water is gone before trees can use much. The rooting zone is the fundamental source of water for the tree. Consequently, changes in root zone water capacity had large effects on transpiration and tree water stress development. This is probably the most difficult parameter in the model to accurately define. Increasing leaf area made little difference on anything except causing higher water stress development, because the soil water was depleted sooner. Decreased leaf area markedly decreased transpiration and water stress and increased subsurface outflow somewhat.

Increased maximum k_l made surprisingly little difference to transpiration; water was used more quickly, but the overall available amount changed very little. This analysis does not reflect results that would be obtained from different sites. On a less water stressed site that retained substantial available soil water at the end of the summer, increased maximum k_l or increased leaf area would cause much higher transpiration.

Table 2.—A sensitivity analysis of DAYTRANS

Independent variables	X(4) Transpiration	X(6) Subsurface outflow	G(10) Predawn leaf ψ
	Dependent variables		
X(1): Snowpack water			
+50%	+2%	+50%	−3%
−50%	−4%	−49%	+4%
B(2): Root zone water			
+50%	+22%	0	−48%
−50%	−45%	0	+40%
B(4): Leaf area			
+50%	+6%	−2%	+25%
−50%	−36%	+7%	−63%
B(5): Maximum k_l			
+50%	+10%	−6%	+21%
−50%	−43%	+3%	−66%
B(6): Interception coeff.			
+50%	0	0	0
−50%	0	+5%	0
B(8): Snowmelt coeff.			
+50%	−2%	+2%	+2%
−50%	+7%	−7%	−10%

The results from the change in interception coefficients are rather artificial because virtually no rain fell during the summer of 1978. During preliminary model runs, it was found that changes in interception can radically change transpiration and water stress predictions. A very low interception rate can cause a small shower to recharge the soil, eliminating all water stress, while, in fact, it requires a rainfall event on the order of 1.5 cm in 24 hours to cause substantial soil recharge in the Fraser stand.

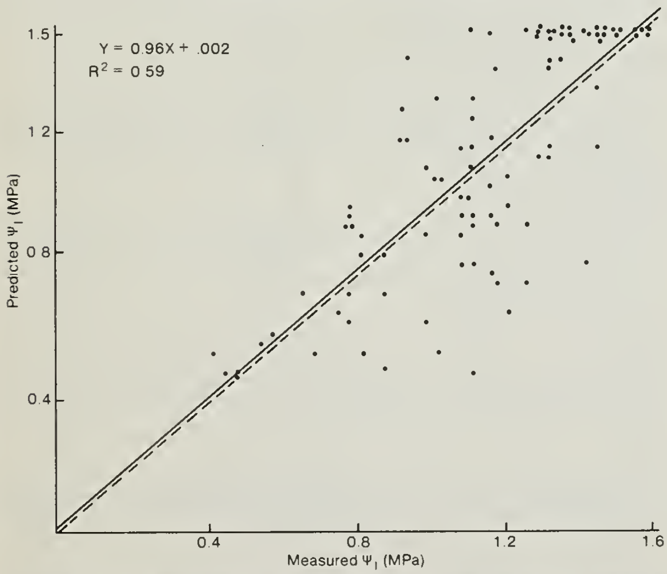

Figure 14.—A summary of all leaf water potentials, ψ_l, measured with a pressure chamber on lodgepole pine at the Fraser site during 1978 compared to predicted ψ_l from the H2OTRANS simulation run. The points represent data taken at all times of the day from sunrise to sunset. The dashed line shows the 1:1 ratio.

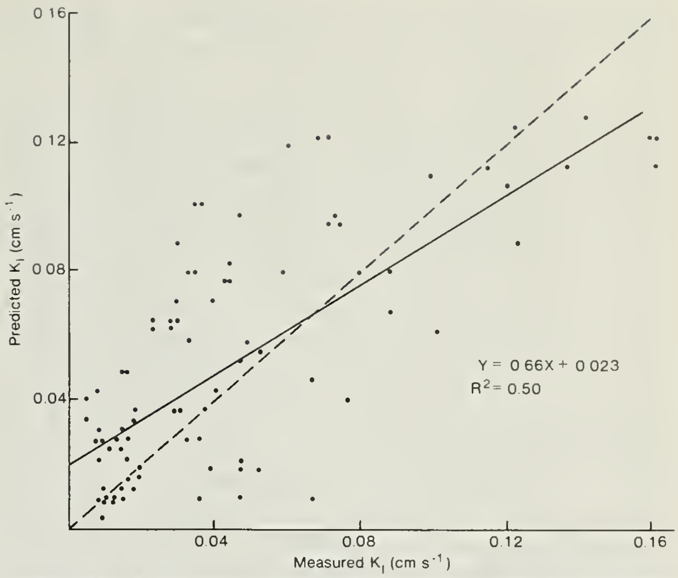

Figure 15.—A summary of all measured crown leaf conductance averages from lodgepole pine on the Fraser site, compared to predicted k_l from the 1978 H2OTRANS simulation run. Each measured point is the average of 9-11 diffusion porometer readings taken throughout the tree crown on foliage ranging from 0 to 3 years old. Sampling was done periodically from sunrise to sunset.

The sensitivity of the snowmelt coefficient also appears to be low, but this could be misleading. A site with a larger snowpack would show higher sensitivity to the influence of the melt rate in partitioning snowmelt to transpiration versus subsurface outflow.

CONCLUSIONS

The preliminary validation of H2OTRANS and DAYTRANS demonstrates that the models are both capable of estimating reasonable water balances for lodgepole pine (fig. 11). The models also appear capable of estimating the physiology of seasonal water stress development in lodgepole pine (figs. 12 and 13). In particular, H2OTRANS is able to track measured ψ_l and k_l diurnally over a wide variety of conditions (figs. 14 and 15). Much of the models' emphasis is on the control of k_l by temperature, radiation, humidity and soil water supply.

The use of morning maximum leaf conductance as a starting point for diurnal k_l calculations seems valuable. The linkage of morning maximum k_l to soil water status through predawn leaf water potential gave fairly accurate results.

The calculation of ψ_l in H2OTRANS is unique and its success (fig. 15) can be attributed to two things. First, the flow resistance used to calculate ψ_l has both a soil temperature and soil moisture component. Second, the flow that generates ψ_l is the root water uptake, not the transpiration rate (which other models have used). This model configuration allows for capacitance in the tree hydraulic system and yields the ψ_l diurnal hysteresis that has been observed in the field by many researchers.

The generality of this ψ_l and k_l paradigm remains uncertain until it can be tested on other species under different conditions.

A primary conclusion from this work has been that prediction of tree water stress development requires more than just accurate physiological response functions. Of equal importance is sound representation of hydrologic inputs and storages. The system inputs and storages control the timing of when water stress begins in the trees. The physiological processes primarily control the subsequent rate of tree water stress development. Interception and surface evaporation losses must be accurate to determine effective precipitation input. Potential errors from these sources were minimized in this validation because the Fraser site had only 7.4 cm of precipitation during the entire summer of 1978. On wetter sites, these processes could profoundly influence the success of a simulation. Of equal importance in model performance is defining the volume of the soil rooting zone, the basic water storage reservoir for the model. This requires knowledge of tree rooting depth and density, averaged for the trees to be modeled.

One avenue of future research could use the models to estimate some of these more difficult parameters. It may be easier to measure transpiration throughout a season, and with the model calculate back to the size of rooting zone that would have been required to sustain the observed activity. Similarly, interception and evaporation losses could be analyzed indirectly by measuring the duration and intensity of precipitation that is necessary before tree water stress recovery can be detected.

Another critical component of water stress modeling is dependable measures of biomass, particularly leaf area, and to a lesser extent, sapwood storage volume. Meteorological driving variables are critical to model performance. It became clear making simultaneous runs of H2OTRANS and DAYTRANS that many problems can develop when averaging meteorological data beyond acceptable limits. Whereas a single daily average soil temperature is fairly reasonable, a daily average incoming radiation value is less so, unless generated by an integrating data-logger. Even then the opportunity to model diurnal radiation thresholds and day length is lost.

With any modeling effort, decisions of temporal and spatial resolution must be balanced against the level of accuracy required. If high resolution predictions of diurnal ψ_l and k_l are required, H2OTRANS should be run on no larger site than a few hectares of even-aged trees, of a single species, on homogeneous topography. For more general seasonal estimates of transpiration and overall stress development, DAYTRANS could provide approximate answers over many hundreds of hectares occupied by a number of tree species.

Given the above considerations, these models have a variety of potential applications. They can provide a physiologically sensitive estimate of evapotranspiration (ET) for hydrologic and meteorologic studies. In studies researching processes sensitive to tree water stress, these models may provide a prediction of water stress.

For example, throughout the western United States forest stands periodically endure water stress sufficient to severely impede photosynthesis. Good correlations between model-predicted site water stress and site productivity (Grier and Running 1977, Running 1981) are likely. There may be a significant correlation between certain insect and disease epidemics and stress development in the host trees (Mattson and Addy 1975, Waring and Pitman 1980). A major component of fire danger rating systems is moisture content of the living fuels. Prediction of plant moisture content must entail a plant water stress model. Quantitative estimates of forest nutrient cycles require knowledge of soil and tree water movement.

These models should be tested on forest stands of varying species, age and structure under different physical and climatic conditions before any general use is attempted. A more extensive validation of H2OTRANS is in progress on eight different stands in southern Wyoming (Knight et al. 1984).

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APPENDIX 1.—Variable Notations.

$B\psi_l$	*predawn* leaf water potential, MPa, treated as positive values in these models
ψ_l	leaf water potential, MPa
k_l	leaf conductance to water vapor diffusion, cm s^{-1}
LA	tree or stand leaf area, cm^2
LAI	leaf area index, the ratio of canopy leaf area to ground area
ABSHD	absolute humidity deficit, g cm^{-3}
T	transpiration rate, cm^3 h^{-1}
TFD	transpiration flux density, g cm^{-2} s^{-1}
PT	potential transpiration, transpiration calculated with the maximum input k_l, cm^3 h^{-1}
R	total water flow resistance in the Soil-Plant-Atmosphere Continuum (SPAC), s cm^{-1}
DAYL	daylength, seconds
RH	relative humidity, %

APPENDIX 2.—Header File Format and Notes for H2OTRANS and DAYTRANS.
H2OTRANS Header File

Mnemonic	Card #	Columns	Format	Description	Default
MAXX	1	1-2	I2	NUMBER OF STATE VARIABLES	-
NEGX[1]		3	I1	OVERRIDE NEG. STATE VAR? 0=NO, 1=YES (DO NOT PRINT DIAGNOSTIC)	0
KSTART		4-6	I3	STARTING TIME	1
KSTOP[2]		7-10	I4	ENDING TIME	365
KSTEP		11-14	I4	TIME INCREMENT(DT)	1
MAXB[3]		16-17	I2	HIGHEST B CONSTANT INDEX	-
MAXG[4]		19-20	I2	TOTAL #G VALUES TO PRINT	-
MAXZ[4]		22-23	I2	TOTAL #Z VALUES TO PRINT	-
KPRINT		25-26	I2	PRINTER INTERVAL	KSTEP
KTHETA[5]		28-29	I2	PRINTER STARTING POINT-INCLUSIVE ITERATIONS FROM BEGINNING	0
NODUMP[6]	1	31-32	I2	"1"=DO NOT DUMP "0"=DUMP	0
JCT	2	14	A4	CARD(DUMP)DECK CODE	"SOWR"
T		5	9A8	TITLE	"STEVE RUNNING"
X(2,I)[7]	3	1-10	E10.4	INITIAL CONDITION STATE VAR #1 (8 PER CARD)	0.0
		11-20	E10.4	INITIAL CONDITION STATE VAR #2 (8 PER CARD)	0.0
B(I)[7,8]	(4)	1-10	E10.4	B(1) CONSTANT (8 PER CARD)	0.0
		11-20	E10.4	B(2) CONSTANT	0.0
IGP(I)[9]	(5)	1-2	I2	INDEX # OF G VALUE TO PRINT (20 MAXIMUM)	-
		3-4	I2		-
IZP(I)[9]	(6)	1-2	I2	INDEX 3 OF Z VALUE TO PRINT (10 MAXIMUM)	-
		3-4	I2		

HEADER FILE NOTES

1. NEGX—If this code is "0," a diagnostic is written for each state variable that becomes negative in value. To disable this diagnostic, type "1" on header record.

2. KSTOP—For hourly resolution model, compute: KSTOP = KSTART + (No. days · 24).

3. MAXB—Always enter the highest index number of B constants actually used.

4. MAXG. MAXZ—This is the total number of G values to print.

5. KTHETA—This feature works in conjunction with KPRINT1. Suppose KSTART = 200, KSTOP = 224, KPRINT = 12, and KTHETA = 0 (default). Printing will occur at 200, 211, and 223 (i.e. hours 1, 12, 24). If KTHETA = 3, printing occurs at 202 and 214 (i.e. hours 3, 15 and 24).

6. NODUMP—If "0," unit 62 must be available for writing upon; if "1," unit 62 is not used.

7. Card #3 begins initial conditions for state variables. With sequential numbering, 1 through 8, the first 8 state variables are initialized. On card #4, #9 through 16 are initialized, etc. Do not leave fields blank until the MAXX (or MAXB) number of variables has been reached. Do not skip any fields, as the processor has no way of determining the index number of the initial value except sequentially, starting with 1.

8. B constants are handled identically as X initial conditions. Values may be read in (punched) as floating point "F FORMAT." E FORMAT is not mandatory. However, some machines require E FORMAT numbers to be punched in a specific way. Check your FORTRAN reference manual at your installation for exact details.

9. These two cards contain the actual index numbers of the variables to print (G and Z variables). The only limitation is that they be less than or equal to the maximum number allowed (20 and 10 respectively for G and Z). The order of printing is as follows:

   X(1) THROUGH X(MAXX) - STATE VARIABLES,
   I(1) THROUGH I(MAXX) - FLOWS,
   $G(i),\ i \in I^G = (IGP(j),\ j = 1,\ MAXG)$
   $Z(i),\ i \in I^Z = (IZP(J),\ J - 1,\ MAXZ)$

   For the G's and Z's, the order of listing is the order of printing, (i.e. there is no resequencing system in the processor to reorder the G's and Z's in a sequential order if they are out of order.)

APPENDIX 3.—Input Format for H2OTRANS Driving Variables, Z(i).

Card	Columns	Format	Variable
1	1-4	A4	Site identification
	5-7	A3	Year
	8-10	F3.0	Julian date
	12-13	A2	Card ID
	14-17	F3.1	Daily precipitation
	18-20	F3.0	Soil temperature
2	1-4	A4	Site ID
	5-7	A3	Year
	8-10	A3	Julian date
	12-13	A3	Card ID
	15-17	F3.1	Incoming shortwave radiation (ly min^{-1})
	18-20	F3.0	Air temperature (°C)
	21-23	F3.0	Relative humidity (%)

Card 2 format is repeated on cards 2 through 5 to give 24 input sets per day on a total of five input cards per day.

APPENDIX 4.—Input Format for DAYTRANS Driving Variables, Z(i).

Card	Columns	Format	Variable
1	1-4	A4	Site ID
	6-7	A2	Year
	9-11	I3	Julian date
	14-16	F3.1	Air temperature (°C)
	18-20	F3.1	Night minimum air temperature (°C)
	22-23	F2.0	Relative humidity (%)
	25-28	F4.0	Average incoming SW radiation (ly min^{-1})
	30-32	F3.1	Soil temperature (°C)
	34-37	F4.2	Precipitation (cm)

One card is needed for each day.

APPENDIX 5.—FORTRAN Listing of H2OTRANS.

```
      REAL*8 FNAM1,FNAM2,FNAM3
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DATA TTY,IN,IN1,IOUT/5,20,21,22/
      WRITE(TTY,5)
    5 FORMAT(' ENTER HEADER INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM1
    6 FORMAT(A10)
      WRITE(TTY,7)
    7 FORMAT(' ENTER DATA INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM2
      WRITE(TTY,8)
    8 FORMAT(' ENTER OUTPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM3
      OPEN(UNIT=IN1,FILE=FNAM1)
      OPEN(UNIT=IN,FILE=FNAM2)
      OPEN(UNIT=IOUT,FILE=FNAM3)
      OPEN(UNIT=23,FILE='PSN.DAT')
C
C        MAIN PROGRAM, CALLS ALL SUBROUTINES
C        SHOULD NOT REQUIRE CHANGE
C
      CALL HEADER(IN1,TTY)
      K=KSTART
   10 CALL ZCOMP(IN)
      CALL PROCES
      CALL PHOTO
      WRITE(23,100) Z(1),G(67)
100   FORMAT(1X,F5.0,1X,F6.1)
      CALL FLOW
      CALL YCOMP
      CALL PRINT(IOUT)
      CALL UPDATE
      IF (K.GT.KSTOP-KSTEP) GO TO 20
      K=K+KSTEP
      GO TO 10
   20 K=KSTOP
      CALL ZERO
      CALL YCOMP
      CALL PRINT(IOUT)
      STOP
      END
      SUBROUTINE HEADER(IN1,TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION IDUM(20)
C
C        READS HEADER INFORMATION CARDS
C        SHOULD NOT REQUIRE CHANGE
C
      READ(IN1,1000) MAXX,NEGX,KSTART,KSTOP,KSTEP,MAXB,MAXG,MAXZ,
     1  KPRINT,KTHETA,NODUMP,JCT,T
 1000 FORMAT(I2,I1,I3,2I4,6I3,/,21A4)
      IF (MAXX.LE.0.OR.MAXX.GT.20) CALL ERROR(5,MAXX,TTY)
      IF (MAXX.GT.16) GO TO 20
      IF (MAXX.GT.8) GO TO 10
```

```
      READ(IN1,1001) (X(2,I),I=1,8)
 1001 FORMAT (8E10.0)
      GO TO 30
   10 READ(IN1,1002) (X(2,I),I=1,16)
 1002 FORMAT (8E10.0,//,8E10.0)
      GO TO 30
   20 READ(IN1,1003) (X(2,I),I=1,20)
 1003 FORMAT (2(8E10.0,/),4E10.0)
   30 IF (MAXB.GT.32) GO TO 70
      IF (MAXB.GT.24) GO TO 60
      IF (MAXB.GT.16) GO TO 50
      IF (MAXB.GT.8) GO TO 40
      IF (MAXB.EQ.0) CALL ERROR(1,0,TTY)
      READ(IN1,2000) (B(I),I=1,8)
 2000 FORMAT (8E10.0)
      GO TO 170
   40 READ(IN1,2001) (B(I),I=1,16)
 2001 FORMAT (8E10.0,//,8E10.0)
      GO TO 170
   50 READ(IN1,2002) (B(I),I=1,24)
 2002 FORMAT (2(8E10.0,/),8E10.0)
      GO TO 170
   60 READ(IN1,2003) (B(I),I=1,32)
 2003 FORMAT (3(8E10.0,/),8E10.0)
      GO TO 170
   70 READ(IN1,2004) (B(I),I=1,40)
 2004 FORMAT (4(8E10.0,/),8E10.0)
  170 IF (MAXG.EQ.0) GO TO 180
      J=21-MAXG
      READ(IN1,3000) (IGP(I),I=1,MAXG),(IDUM(I),I=1,J)
 3000 FORMAT (21I2)
  180 J=11-MAXZ
      IF (MAXZ.EQ.0) GO TO 190
      READ(IN1,3001) (IZP(I),I=1,MAXZ),(IDUM(I),I=1,J)
 3001 FORMAT (11I2)
  190 IF (KSTART.EQ.0) KSTART=1
      IF (KSTOP.EQ.0) KSTOP=365
      IF (KSTEP.EQ.0) KSTEP=1
      IF (KPRINT.EQ.0) KPRINT=KSTEP
      IF (JCT.EQ.'    ') JCT='SCWR'
      DO 200 I=1,20
      IF (T(I).NE.'    ') GO TO 210
  200 CONTINUE
      T(1)='STEV'
      T(2)='E RU'
      T(3)='NNIN'
      T(4)='G   '
  210 RETURN
      END
      SUBROUTINE ZCOMP(IN)
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20)
C
C          READS CLIMATIC DATA CARDS
C          CHANGES IN CLIMATIC DATA INPUT FORMAT GO HERE
C       *  Z FUNCTIONS GO HERE
C       *  Z    DESCRIPTION
C          -    -----------
C          1    JULIAN DAY
C          2    PRECIPITATION (CM)
C          3    AIR TEMPERATURE (C)
```

```
C         4    RELATIVE HUMIDITY (PER CENT)
C         5    SOIL TEMPERATURE (C)
C         6    RADIATION (AVE. LANGLEYS PER MIN)
C         7    DAYLENGTH (SUNRISE-SUNSET)
C         8    NIGHT MINIMUM AIR TEMP. (C)
C
  100 FORMAT(8X,I3,F5.1,F4.1,F3.0,F5.2,F4.1,F5.2)
      READ(IN,100,END=50) JD,XTAIR,XTMIN,XRHUM,XRAD,XTSOIL,XPPT
      Z(1)=JD
      Z(2)=XPPT
      Z(3)=XTAIR
        ESD=6.1078*EXP((17.269*Z(3))/(237.3+Z(3)))
        ES=XRHUM/100.*ESD
        VPD=AMAX1((ESD-ES),0.0)
      Z(4)=217.E-6*VPD/(Z(3)+273.16)
      Z(5)=XTSOIL
      Z(6)=XRAD
        XD=JD-79.
        IF(XD .LT. 0.0)   XD=286.0+JD
        DAY=3.125*(SIN(XD*0.01721))+12.0
      Z(7)=DAY*3600*0.8
      Z(8)=XTMIN
      Z(12)=XRHUM
      Z(11)=VPD
   50 RETURN
      END
      SUBROUTINE UPDATE(TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),DUM(380),MAXX,DUMM(47),NEGX
C
C          UPDATES STATE VARIABLES (COMPARTMENTS) AFTER EACH ITERATION
C          SHOULD NOT REQUIRE CHANGE
C
      DO 10 I=1,MAXX
      L=I
      X(2,I)=X(2,I)+X(1,I)
      IF (X(2,I).LT.0..AND.NEGX.EQ.0) CALL ERROR(2,L,TTY)
   10 CONTINUE
      RETURN
      END
      SUBROUTINE YCOMP
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ
C
C          PREPARES MATRIX OF COMPUTED VALUES FOR PRINTOUT
C          SHOULD NOT REQUIRE CHANGE
C
      DO 10 I=1,MAXX
      J=I+MAXX
      Y(I)=X(2,I)
   10 Y(J)=X(1,I)
      MAX2=2*MAXX
      DO 20 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
   20 Y(J)=G(L)
      MAX3=MAX2+MAXG
      DO 30 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
```

```
   30 Y(J)=Z(L)
      RETURN
      END
      SUBROUTINE ERROR(I,J,TTY)
      INTEGER TTY
C
C        LIBRARY OF ERROR STATEMENTS CALLED WHEN MISTAKES ARE
C        MADE IN OTHER PART OF THE PROGRAM
C        SHOULD NOT REQUIRE CHANGE
C
      IF (I.LE.0 .OR. I.GE.8) GO TO 99
      GO TO (1,2,3,4,5,6,7),I
    1 WRITE(TTY,1001)
 1001 FORMAT(' ERROR IN B CONSTANTS.  MAXB=0',/)
      STOP
    2 WRITE(TTY,1002) J
 1002 FORMAT(' ERROR IN SUB. UPDATE - X(',I2,').LT.0.',/)
      RETURN
    3 WRITE(TTY,1003) J
 1003 FORMAT(' ERROR IN SUB. PROCESS.  G(',I2,') IS LT 0.',/)
      RETURN
    4 WRITE(TTY,1004) J
 1004 FORMAT(' ERROR IN SPECIAL FUNCTION (',I2,')',/)
      RETURN
    5 WRITE(TTY,1005) J
 1005 FORMAT(' ERROR IN NO. STATE VARIABLES.  MAXX=',I3,/)
      STOP
    6 WRITE(TTY,1006)
 1006 FORMAT(' ERROR IN YCOMP',/)
      RETURN
    7 WRITE(TTY,1007)
 1007 FORMAT(' ERROR IN SUB. ZCOMP.',/)
      RETURN
   99 WRITE(TTY,9000)  I
 9000 FORMAT (1H-,'ERROR IN SUB. ERROR.  ERROR CODE=',I3)
      END
      SUBROUTINE  FLOW
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
C
C        COUPLES FLOW BETWEEN COMPARTMENTS
C        NEW COMPARTMENTS OR NEW COUPLING BETWEEN COMPARTMENTS MUST GO HERE
C
      DO 10 I=1,20
      DO 10 J=1,20
      F(I,J)=0.0
   10 CONTINUE
      DO 20 I=1,MAXX
      X(I)=XS(2,I)
   20 CONTINUE
C
C     *  FLOW FUNCTIONS GO HERE
C
      F( 1, 2)=G(50)
      F( 2, 2)=G(1)
      F( 2, 3)=G(53)
      F( 2, 5)=G(51)
      F( 2, 6)=G(52)
      F( 3, 4)=G(29)
      F( 7, 7)=G(9)
```

```
      F( 8, 8)=G(62)
      F( 9, 9)=G(66)
      F(10,10)=G(67)
      DO 30 I=1,MAXX
      XS(1,I)=0.0
   30 CONTINUE
      DO 50 I=1,MAXX
      DO 50 J=1,MAXX
      PART=F(J,I)-F(I,J)
      IF (I.EQ.J) PART=F(I,I)
   50 XS(1,I)=XS(1,I)+PART
      RETURN
      END
      SUBROUTINE PROCES
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
C
C        AUXILIARY EQUATIONS USED IN THE STRUCTURE OF THE MODEL
C
      IF (IFLAG.NE.0) GO TO 20
      IFLAG=1
      DO 10 I=1,100
      G(I)=-1.0E32
   10 CONTINUE
   20 DO 30 I=1,MAXX
      X(I)=XS(2,I)
   30 CONTINUE
C
C     *  G FUNCTIONS GO HERE
C
      G(1)=AMAX1((Z(2)-(B(4)/B(7))*B(6))*B(7),0.0)
      G(2)=X(2)/B(2)
      G(3)=X(3)/B(3)
      G(4)=AMAX1(B(8)*Z(3)*B(7),0.0)
        IF(X(1) .LE. 0.0)  G(4)=0.0
      G(5)=B(4)/B(7)
      G(9)=Z(2)*B(7)-G(1)
      G(10)=AMAX1(B(10),0.2/G(2)+0.01*B(9),0.0)
      G(12)=10.*(1.0-EXP(-4.6*Z(6)))
      G(13)=1.-((G(5)-G(12))/G(5))
        IF(G(12) .GT. G(5)) G(13)=1.0
      G(14)=B(5)-(B(5)/(B(11)-B(10)))*(G(10)-B(10))
        IF(G(10) .GE. B(11)) G(14)=0.005
      G(15)=G(14)-(G(14)*0.05*(Z(4)*1.0E+6-4.0))
        IF(G(15) .LE. 0.0) G(15)=0.005
      G(16)=G(15)+G(15)*0.003*(Z(3)-10.0)
        IF(Z(8) .LT. 0.0) G(16)=AMAX1(G(15)+0.02*Z(8),0.005)
      G(17)=G(16)*G(13)
      G(18)=Z(4)*G(17)
      G(19)=G(18)*B(4)*Z(7)
      G(20)=G(17)/B(5)
      G(21)=G(19)/B(7)*10.
      G(50)=G(4)
        IF(X(1)-G(4) .LT. 0.0)  G(50)=X(1)
      G(51)=0.0
        IF((G(1)+G(4))/B(7) .GT. B(1))  G(51)=(G(50)-B(1))*B(7)
      G(52)=0.0
        IF(X(2)+G(50) .GT. B(2))  G(52)=X(2)+G(50)-G(51)-B(2)
      G(53)=B(3)-X(3)+G(19)
      G(55)=0.0
```

```
C
C   PENMON FUNCTION
C
       G(28)=PENMON(Z(3),Z(6),Z(11),G(5),G(17))
       G(29)=G(28)*B(4)*Z(7)
C
       RETURN
       END
       SUBROUTINE PHOTO
       COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160)
C
C         Z(10) = CANOPY AVERAGE RADIATION
C
       Z(10)=(Z(6)+Z(6)*EXP(-0.7*G(5)/2.))/2.
C
C         Z(9) = AVERAGE NIGHT TEMPERATURE
C
       Z(9)=(Z(3) + Z(8))/2.
C
       G(64)=((Z(10)-0.0143)/(Z(10)+0.322))*
     C(0.0182+0.0105*Z(3)-0.000194*(Z(3)**2))
       IF(G(64).LT.0.)G(64)=0.
       G(65)=(0.0006*(G(17)/1.6)*G(64))/
     C((G(17)/1.6)+G(64))
       G(62)=0.001*(24.-Z(7)/3600.)*EXP(0.2*Z(9))
       G(66)=G(65)*Z(7)
       G(67)=G(66)-G(62)
       RETURN
       END
       SUBROUTINE ZERO
       COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20)
C
C          ZEROS PARAMETERS IN MODEL
C          SHOULD NOT REQUIRE CHANGE
C
       DO 20 I=1,20
       X(1,I)=0.
       Z(I)=0.
       DO 20 J=1,20
    20 F(I,J)=0.0
       DO 30 I=1,100
    30 G(I)=0.0
       RETURN
       END
       SUBROUTINE PRINT(IOUT)
       COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
       DIMENSION XNULL(100),LBL(100,2),JK(10)
       DATA JK/1,8,15,22,29,36,43,50,57,64/
C
C          LABELS LINE PRINTER OUTPUT
C          ESTABLISHES OUTPUT FORMAT
C          PRINTS OUT ALL REQUESTED PARAMETERS
C          SHOULD NOT REQUIRE CHANGE
C
       IF (IFLAG.EQ.1) GO TO 30
       IFLAG=1
       DO 10 I=1,100
       XNULL(I)=0.0
```

```
      DO 10 J=1,2
   10 LBL(I,J)=' '
      J=100-MAXB
      WRITE (IOUT,1000) T,MAXX,(B(I),I=1,MAXB),
     1 (XNULL(I),I=1,J),KSTART,KSTOP,KSTEP
 1000 FORMAT('1',/,'1',/,5X,'KXBZ SIMULATION PROCESSOR',/,5X,20A4,/,
     1 5X,'STATE VARIABLES=',I2,/,5X,'B CONSTANTS=',/,
     2 10(5X,10(1X,1PG11.4),/),5X,'INITIAL TIME',3X,I3,/,5X,
     3 'TERMINATION',4X,I3,/,5X,'INCREMENT (DT)',1X,I3)
      MAX2=2*MAXX
      MAX3=MAX2+MAXG
      MY=MAX3+MAXZ
      JJ=100-MY
      IF (MY.LE.50) JJ=JJ-50
      DO 20 I=1,MY
      IF (I.LE.MAXX) LBL(I,1)='X('
      IF (I.GT.MAXX.AND.I.LE.MAX2) LBL(I,1)='I('
      IF (I.GT.MAX2.AND.I.LE.MAX3) LBL(I,1)='G('
      IF (I.GT.MAX3.AND.I.LE.MY) LBL(I,1)='Z('
   20 CONTINUE
      DO 21 I=1,MAXX
      ENCODE(3,2002,LBL(I,2)) I
 2002 FORMAT(I2,')')
   21 CONTINUE
      DO 22 I=1,MAXX
      J=MAXX+I
      ENCODE(3,2002,LBL(J,2)) I
   22 CONTINUE
      DO 23 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
      ENCODE(3,2002,LBL(J,2)) L
   23 CONTINUE
      DO 24 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
      ENCODE(3,2002,LBL(J,2)) L
   24 CONTINUE
   30 IF (KFLAG.EQ.1) GO TO 40
      KFLAG=1
      ICT=0
      WRITE(IOUT,2000) T
 2000 FORMAT('1',/,5X,20A4,/)
      WRITE(IOUT,2001) ((LBL(I,J),J=1,2),I=1,100)
 2001 FORMAT('    TIME',10(7X,A2,A3),/,9(8X,10(7X,A2,A3),/))
      ICT=ICT+15
   40 IF (MOD(K-KSTART+1+KPRINT-KTHETA,KPRINT).NE.0) GO TO 60
      IF (MY.LE.50) GO TO 50
      WRITE (IOUT,3000) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3000 FORMAT(3X,I4,10(1X,1PG11.4),/,9(7X,10(1X,1PG11.4),/))
      ICT=ICT+11
      GO TO 60
   50 WRITE (IOUT,3001) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3001 FORMAT(3X,I4,10(1X,1PG11.4),/,4(7X,10(1X,1PG11.4),/))
      ICT=ICT+6
   60 IF (ICT.GT.50) KFLAG=0
      IF (NODUMP.EQ.1) RETURN
      OPEN(UNIT=23,FILE='DUMP.DAT')
      KK=0
      DO 70 I=1,MY,7
```

```
      J1=I
      J2=I+6
      KK=KK+1
      WRITE(23,4000) JCT,K,JK(KK),(Y(L),L=J1,J2)
 4000 FORMAT (A4,I4,1X,I2,7E10.3)
   70 CONTINUE
      RETURN
      END
      FUNCTION PENMON(TAIR,RAD,VPD,XLAI,COND)
      GAMMA=0.646+0.0006*TAIR
      PLAI=XLAI/2.
      T1=TAIR+0.5
      T2=TAIR-0.5
      SVP1=6.1078*EXP((17.269*T1)/(237.0+T1))
      SVP2=6.1078*EXP((17.269*T2)/(237.0+T2))
      SLOPE=SVP1-SVP2
      XNETR=RAD*0.8*697.3
      CP=1.01E+3
      PA=1.292-0.00428*TAIR
      RA=5.0
      RS=100./COND
      XLAT=(2.501 - 0.0024*TAIR) * 1.0E+6
      XTRANS=((SLOPE*XNETR)/PLAI+(CP*PA)*(VPD/RA))/
     C(SLOPE+GAMMA*(1.0+RS/RA))
      PENMON=XTRANS/(XLAT * 10.)
      RETURN
      END
      FUNCTION S4(K)
C
C          SETS MODEL STARTING POINT TO REQUESTED JULIAN DATE
C          REGARDLESS OF DATA.
C          SHOULD NOT REQUIRE CHANGE
C
      IN=20
   10 READ(IN,1000,END=20) KD
 1000 FORMAT( 7X,I3)
      IF (K.GT.KD) GO TO 10
      BACKSPACE IN
      S4=1.
      RETURN
   20 REWIND IN
      IFLAG=IFLAG+1
      IF (IFLAG.EQ.2) STOP
      GO TO 10
      END
```

```
C     DATA FILE INPUT STATEMENTS
C
      REAL*8 FNAM1,FNAM2,FNAM3
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DATA TTY,IN,IN1,IOUT/5,20,21,22/
      WRITE(TTY,5)
    5 FORMAT(' ENTER HEADER INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM1
    6 FORMAT(A10)
      WRITE(TTY,7)
    7 FORMAT(' ENTER DATA INPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM2
      WRITE(TTY,8)
    8 FORMAT(' ENTER OUTPUT FILE NAME(MAX 10 CHAR): ',$)
      READ(TTY,6) FNAM3
      OPEN(UNIT=IN1,FILE=FNAM1)
      OPEN(UNIT=IN,FILE=FNAM2)
      OPEN(UNIT=IOUT,FILE=FNAM3)
C
C     MAIN PROGRAM, CALLS SUBROUTINES
C
      CALL HEADER(IN1,TTY)
      K=KSTART
   10 CALL ZCOMP
      CALL PROCES
      CALL FLOW
      CALL YCOMP
      IF(Z(6).EQ. 0.0) GO TO 15
      CALL PRINT(IOUT)
   15 CONTINUE
      CALL UPDATE(TTY)
      IF (K.GT.KSTOP-KSTEP) GO TO 20
      K=K+KSTEP
      GO TO 10
   20 K=KSTOP
      CALL ZERO
      CALL YCOMP
      CALL PRINT(IOUT)
      STOP
      END
C
      SUBROUTINE HEADER(IN1,TTY)
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION IDUM(20)
      READ(IN1,1000) MAXX,NEGX,KSTART,KSTOP,KSTEP,MAXB,MAXG,MAXZ,
     1  KPRINT,KTHETA,NODUMP,JCT,T
 1000 FORMAT(I2,I1,I3,2I4,6I3,/,21A4)
      IF (MAXX.LE.0 .OR. MAXX.GT.20) CALL ERROR (5,MAXX,TTY)
      IF (MAXX.GT.16) GO TO 20
      IF (MAXX.GT.8) GO TO 10
      READ(IN1,1001) (X(2,I),I=1,8)
 1001 FORMAT (8E10.0)
      GO TO 30
   10 READ(IN1,1002) (X(2,I),I=1,16)
 1002 FORMAT (8E10.0,/,8E10.0)
```

```
      GO TO 30
   20 READ(IN1,1003) (X(2,I),I=1,20)
 1003 FORMAT (2(8E10.0,/),4E10.0)
   30 IF (MAXB.GT.32) GO TO 70
      IF (MAXB.GT.24) GO TO 60
      IF (MAXB.GT.16) GO TO 50
      IF (MAXB.GT.8) GO TO 40
      IF (MAXB.EQ.0) CALL ERROR(1,0,TTY)
      READ(IN1,2000) (B(I),I=1,8)
 2000 FORMAT (8E10.0)
      GO TO 170
   40 READ(IN1,2001) (B(I),I=1,16)
 2001 FORMAT (8E10.0,/,8E10.0)
      GO TO 170
   50 READ(IN1,2002) (B(I),I=1,24)
 2002 FORMAT (2(8E10.0,/),8E10.0)
      GO TO 170
   60 READ(IN1,2003) (B(I),I=1,32)
 2003 FORMAT (3(8E10.0,/),8E10.0)
      GO TO 170
   70 READ(IN1,2004) (B(I),I=1,40)
 2004 FORMAT (4(8E10.0,/),8E10.0)
  170 IF (MAXG.EQ.0) GO TO 180
      J=21-MAXG
      READ(IN1,3000) (IGP(I),I=1,MAXG),(IDUM(I),I=1,J)
 3000 FORMAT (21I2)
  180 J=11-MAXZ
      IF (MAXZ.EQ.0) GO TO 190
      READ(IN1,3001) (IZP(I),I=1,MAXZ),(IDUM(I),I=1,J)
 3001 FORMAT (11I2)
  190 IF (KSTART.EQ.0) KSTART=1
      IF (KSTOP.EQ.0) KSTOP=365
      IF (KSTEP.EQ.0) KSTEP=1
      IF (KPRINT.EQ.0) KPRINT=KSTEP
      IF (JCT.EQ.4H    ) JCT=4HSOWR
      DO 200 I=1,9
      IF (T(I).EQ.8H        ) GO TO 200
      GO TO 210
  200 CONTINUE
      T(1)='STEV'
      T(2)='E RU'
      T(3)='NNIN'
      T(4)='G   '
  210 CONTINUE
      RETURN
      END
C
      SUBROUTINE ZCOMP
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20)
C
C     *   Z    DESCRIPTION
C         -    -----------
C         1    JULIAN DAY
C         2    PRECIPITATION (CM)
C         3    AIR TEMPERATURE (C)
C         4    RELATIVE HUMIDITY (%)
C         5    SOIL TEMP (C)
C         6    RADIATION (LANGLEYS PER MIN)
C         7    HOUR OF DAY
      DIMENSION VAL(10,24)
```

```
      IF (IFLAG.NE.0) GO TO 10
      IFLAG=1
      XI=S4(K)
      IF (XI.NE.1.) STOP
   10 CONTINUE
C
C     *  Z FUNCTIONS GO HERE
C
      XI = S2( VAL (1,1) )
      Z(1) = VAL(1,1)
      Z(2) = VAL(2,1)
      Z(3) = VAL(5,1)
      Z(4) = VAL(6,1)
      Z(5) = VAL(3,1)
      Z(6) = VAL(4,1)
      Z(7) = Z(7) + 1.0
      IF (Z(7) .GE. 25.0)  Z(7) = 1.0
      RETURN
      END
C
      SUBROUTINE UPDATE(TTY)
      INTEGER TTY
      COMMON K,X(2,20),F(20,20),DUM(380),MAXX,DUMM(47),NEGX
      DO 10 I=1,MAXX
      L=I
      X(2,I)=X(2,I)+X(1,I)
      IF (X(2,I).LT.0. .AND. NEGX.EQ.0) CALL ERROR(2,L,TTY)
   10 CONTINUE
      RETURN
      END
C
      SUBROUTINE YCOMP
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ
      DO 10 I=1,MAXX
      J=I+MAXX
      Y(I)=X(2,I)
      Y(J)=X(1,I)
   10 CONTINUE
      DO 20 I=1,MAXG
      J=2*MAXX+I
      L=IGP(I)
      Y(J)=G(L)
   20 CONTINUE
      DO 30 I=1,MAXZ
      J=2*MAXX+MAXG+I
      L=IZP(I)
      Y(J)=Z(L)
   30 CONTINUE
      RETURN
      END
C
      SUBROUTINE ERROR (I,J,TTY)
      INTEGER TTY
      IF (I.LE.0 .OR. I.GE.8) GO TO 99
      GO TO (1,2,3,4,5,6,7),I
    1 WRITE(TTY,1001)
 1001 FORMAT(1H0,'ERROR IN B CONSTANTS.  MAXB=0',/)
      STOP
    2 WRITE(TTY,1002) J
```

```
 1002 FORMAT (1H0,'ERROR IN SUB. UPDATE - X(',I2,').LT.0.',/)
      RETURN
    3 WRITE(TTY,1003) J
 1003 FORMAT (1H0,'ERROR IN SUB. PROCES.  G(',I2,') IS LT 0.',/)
      RETURN
    4 WRITE(TTY,1004) J
 1004 FORMAT (1H0,'ERROR IN SPECIAL FUNCTION (',I2,')',/)
      RETURN
    5 WRITE(TTY,1005) J
 1005 FORMAT (1H0,'ERROR IN NO. STATE VARIABLES.  MAXX=',I3,/)
      STOP
    6 WRITE(TTY,1006)
 1006 FORMAT (1H0,'ERROR IN YCOMP',/)
      RETURN
    7 WRITE(TTY,1007)
 1007 FORMAT (1H0,'ERROR IN SUB. ZCOMP.',/)
      RETURN
   99 WRITE(TTY,9000)  I
 9000 FORMAT (1H-,'ERROR IN SUB. ERROR.  ERROR CODE=',I3)
      END
C
      SUBROUTINE  FLOW
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
      DO 10 I=1,20
      DO 10 J=1,20
      F(I,J)=0.0
   10 CONTINUE
      DO 20 I=1,MAXX
      X(I)=XS(2,I)
   20 CONTINUE
C
C     *  FLOW FUNCTIONS GO HERE
C
      F(3,3)=G(50)-G(53)
      F(1,3)=G(51)
      F(3,2)=G(54)
      F(3,4)=G(55)
      F(4,5)=G(56)
      F(5,6)=G(57)
      F(8,9)=G(18)
      F(7,8)=G(62)
      F(4,7)=G(67)
      F(5,7)=G(68)
      F(10,10)=G(53) + G(58)
      DO 30 I=1,MAXX
      XS(1,I)=0.0
   30 CONTINUE
      DO 50 I=1,MAXX
      DO 40 J=1,MAXX
      IF (I.EQ.J) GO TO 60
      XS(1,I)=XS(1,I)+F(J,I)-F(I,J)
   40 CONTINUE
   50 CONTINUE
      RETURN
   60 XS(1,I)=XS(1,I)+F(I,I)
      GO TO 40
      END
C
      SUBROUTINE PROCES
```

```
      COMMON K,XS(2,20),F(20,20),G(100),B(100),Z(20),DUM(160),MAXX
      DIMENSION X(20)
      IF (IFLAG.NE.0) GO TO 20
      IFLAG=1
      DO 10 I=1,100
      G(I)=-1.0E32
   10 CONTINUE
   20 DO 30 I=1,MAXX
      X(I)=XS(2,I)
   30 CONTINUE
C
C     *  G FUNCTIONS GO HERE
C
      G(1)=S3(Z(3),Z(4))
      G(2)=B(9)/B(10)
      G(3)=X(3)/B(3)
      G(4)=X(4)/B(4)
      G(5)=X(5)/B(5)
      G(6)=(G(4)+G(5))/2.
      G(7)=X(7)/B(7)
      G(10)=AMAX1(B(13),0.2/G(6)+0.01*B(11),0.0)
      G(11)=10.*(1.0-EXP(-4.6*Z(6)))
      G(12)=1.0-(G(2)-G(11))/G(2)
      IF(G(11).GT.G(2)) G(12)=1.0
      G(13)=AMAX1(B(12)-(B(12)/(B(14)-B(13)))*(G(10)-B(13)),0.005)
      IF(G(10).LT.B(13)) G(13)=B(12)
      G(14)=G(13)-(G(13)*.05*(G(1)*1.0E6-4.))
      IF(G(14) .LE. 0.0) G(14)=0.005
      G(15)=S1(Z(3),Z(7),G(14))
      G(16)=G(15)*G(12)
      G(17)=G(16)*G(1)
      G(18)=G(17)*B(9)*3600.
C
      IF(Z(7) .GT. 4.)Z(2)=0.0
      G(50)=AMAX1((Z(2)/4.-B(6)*(B(9)/B(10)))*B(10),0.0)
      G(51)=AMIN1(Z(3)*B(1)*B(10),X(1))
      IF(Z(3).LE.0.0) G(51)=0.0
      G(52)=EXP(5.*(G(3)-1.0))
      G(53)=G(52)*G(1)*B(10)*3600.
      IF(G(3).LE.0.0) G(53)=0.
      IF(X(1).GT.0.) G(53)=0.
      G(54)=AMAX1((G(50)+G(51)-(B(2)*B(10))),0.)
      G(55)=AMAX1((G(50)+G(51)-G(53)-G(54))-(B(3)-X(3)),0.0)
      G(56)=AMAX1(G(55)-(B(4)-X(4)),0.0)
      G(57)=AMAX1(G(56)-(B(5)-X(5)),0.0)
      G(58)=(Z(2)/4.)*B(10)-G(50)
C
      G(60)=B(8)*(1.-G(10)/B(14)+B(13)/B(14))
      G(61)=X(8)/B(16)
      G(62)=0.
      IF(G(61).GE.G(18)) G(62)=AMAX1(G(60)-X(8),G(18)/B(16))
      IF(G(61).LT.G(18)) G(62)=G(18)-G(61)
      G(66)=X(7)/B(17)
      G(67)=AMIN1(G(62)-G(66),(B(7)-X(7))/B(17),X(4)/B(17))
      G(68)=AMIN1(G(62)-G(66)-G(67),(B(7)-X(7))/B(17))
      G(69)=G(67)+G(68)
C
      IF(Z(5) .LT. 0.0)G(70)=10.0
      IF(Z(5) .GT. 0.0) G(70)=1.0/Z(5)
      G(71)=-0.28+2.*G(10)
```

```
      G(72)=G(70)+G(71)
      G(73)=AMIN1(G(10)+G(72)*(G(69)*278./B(9)),B(14))
      G(76)=G(16)/B(12)
      G(77)=G(18)/B(10)*10.
      G(78)=0.0
      RETURN
      END
C
      SUBROUTINE ZERO
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20)
      DO 10 I=1,20
      X(1,I)=0.0
      Z(I)=0.0
   10 CONTINUE
      DO 20 I=1,20
      DO 20 J=1,20
      F(I,J)=0.0
   20 CONTINUE
      DO 30 I=1,100
      G(I)=0.0
   30 CONTINUE
      RETURN
      END
C
      SUBROUTINE PRINT(IOUT)
      COMMON K,X(2,20),F(20,20),G(100),B(100),Z(20),Y(160),MAXX,MAXB,
     1 KSTART,KSTOP,KSTEP,IGP(20),IZP(10),KPRINT,MAXG,MAXZ,T(20),JCT,
     2 NEGX,KTHETA,NODUMP
      DIMENSION XNULL(100),LBL(100,2),JK(10)
      DATA JK/1,8,15,22,29,36,43,50,57,64/
      IF (IFLAG.EQ.1) GO TO 30
      IFLAG=1
      DO 10 I=1,100
      XNULL(I)=0.0
      DO 10 J=1,2
   10 LBL(I,J)=' '
      J=100-MAXB
      WRITE(IOUT,1000) T,MAXX,(B(I),I=1,MAXB),
     1 (XNULL(I),I=1,J),KSTART,KSTOP,KSTEP
 1000 FORMAT ('1',/,'1',/,5X,'KXBZ SIMULATION PROCESSOR',/,5X,20A4,/,
     1 5X,'STATE VARIABLES=',I2,/,5X,'B CONSTANTS=',/,
     2 10(5X,10(1X,1PG11.4),/),5X,'INITIAL TIME',3X,I4,/,5X,
     3 'TERMINATION',4X,I4,/,5X,'INCREMENT (DT)',1X,I4)
      MAX2=2*MAXX
      MAX3=MAX2+MAXG
      MY=MAX3+MAXZ
      JJ=100-MY
      IF (MY.LE.50) JJ=JJ-50
      DO 20 I=1,MY
      IF (I.LE.MAXX) LBL(I,1)='X('
      IF (I.GT.MAXX.AND.I.LE.MAX2) LBL(I,1)='I('
      IF (I.GT.MAX2.AND.I.LE.MAX3) LBL(I,1)='G('
      IF (I.GT.MAX3.AND.I.LE.MY) LBL(I,1)='Z('
   20 CONTINUE
      DO 21 I=1,MAXX
      ENCODE (3,2002,LBL(I,2)) I
 2002 FORMAT(I2,')')
   21 CONTINUE
      DO 22 I=1,MAXX
      J=MAXX+I
```

```
      ENCODE (3,2002,LBL(J,2)) I
   22 CONTINUE
      DO 23 I=1,MAXG
      J=MAX2+I
      L=IGP(I)
      ENCODE (3,2002,LBL(J,2)) L
   23 CONTINUE
      DO 24 I=1,MAXZ
      J=MAX3+I
      L=IZP(I)
      ENCODE (3,2002,LBL(J,2)) L
   24 CONTINUE
   30 IF (KFLAG.EQ.1) GO TO 40
      KFLAG=1
      ICT=0
      WRITE(IOUT,2000) T
 2000 FORMAT('1',5X,20A4,/)
      WRITE(IOUT,2001) ((LBL(I,J),J=1,2),I=1,100)
 2001 FORMAT (4X,'TIME',10(3X,A2,A3,4X),/,9(8X,10(3X,A2,A3,4X),/))
      ICT=ICT+13
   40 IF (MOD(K-KSTART+1+KPRINT-KTHETA,KPRINT).NE.0) GO TO 60
      IF (MY.LE.50) GO TO 50
      WRITE(IOUT,3000) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3000 FORMAT (3X,I4,10(1X,1PG11.4),/,9(7X,10(1X,1PG11.4),/))
      ICT=ICT+11
      GO TO 60
   50 WRITE(IOUT,3001) K,(Y(I),I=1,MY),(XNULL(I),I=1,JJ)
 3001 FORMAT(3X,I4,10(1X,1PG11.4),/,4(7X,10(1X,1PG11.4),/))
      ICT=ICT+6
   60 IF (ICT.GT.50) KFLAG=0
      IF (NODUMP.EQ.1) RETURN
      OPEN(UNIT=23,FILE='DUMP.DAT')
      KK=0
      DO 70 I=1,MY,7
      J1=I
      J2=I+6
      KK=KK+1
      WRITE (23,4000) JCT,K,JK(KK),(Y(L),L=J1,J2)
 4000 FORMAT (A4,I4,1X,I2,7E10.3)
   70 CONTINUE
      RETURN
      END
C
      FUNCTION S1(TAIR,XHOUR,COND)
      IF(XHOUR-5.) 91,90,91
 90   SRT=TAIR
 91   IF(SRT.GT.0) GO TO 92
      S1=AMAX1(COND+0.02*SRT,0.005)
      IF(SRT.LT.-7.) S1=0.005
      GO TO 93
 92   S1=COND+COND*0.003*(TAIR-10.0)
 93   RETURN
      END
C
      FUNCTION S2 (VAL)
      DIMENSION VAL(10,24)
      IN=20
      IF (IFLAG.EQ.1) GO TO 20
      READ (IN,1000) (VAL(I,1),I=1,3),((VAL(I,J),I=4,6),J=1,6),
     1 ((VAL(I,J),I=4,6),J=7,12),((VAL(I,J),I=4,6),J=13,18),
```

```
     2 ((VAL(I,J),I=4,6),J=19,24)
 1000 FORMAT (7X,F3.0,4X,F3.1,F3.0,/,3(14X,6(F3.1,2F3.0),/),
     1 14X,6(F3.1,2F3.0))
    6 K=1
      IFLAG=1
      DO 10 I=2,24
      VAL(1,I)=VAL(1,1)
      VAL(2,I)=VAL(2,1)
      VAL(3,I)=VAL(3,1)
   10 CONTINUE
      S2=1.
      K = K + 1
      RETURN
   20 DO 40 J=1,10
      DO 30 I=2,24
      VAL(J,I-1)=VAL(J,I)
   30 CONTINUE
      VAL(J,24)=0.0
   40 CONTINUE
      IF (K.EQ.24) IFLAG=0
      K=K+1
      S2=2.
      RETURN
      END
C
      FUNCTION S3(TA,RH)
C     ******ABSOLUTE HUMIDITY DEFICIT (AIR TEMP, REL HUM)
      ESD = 6.1078 * EXP ((17.269 * TA)/ (237.3 + TA))
      ES=RH/100.*ESD
C     ******   IN THE EVENT DEW IS GTP THAN AIR, RETURN ZERO
      VPD = AMAX1((ESD - ES), 0.0)
      S3= 217.E-6 * VPD / (TA + 273.16)
      RETURN
      END
C
      FUNCTION S4(K)
      IN=20
   10 READ (IN,1000,END=20) KD
 1000 FORMAT( 7X,I3)
   15 IF (K.GT.KD) GO TO 10
      BACKSPACE IN
      S4=1.
      RETURN
   20 REWIND IN
      IFLAG=IFLAG+1
      IF (IFLAG.EQ.2) STOP
      GO TO 10
      END
```


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Running, Steven W. 1984. Documentation and preliminary validation of H2OTRANS and DAYTRANS, two models for predicting transpiration and water stress in western coniferous forests. USDA Forest Service Research Paper RM-252, 45 p. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.

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Keywords: Ecosystem model, hydrology model, tree water stress, computer simulation, transpiration model, water potential, leaf conductance

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Rocky
Mountains

Southwest

Great
Plains

U.S. Department of Agriculture
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Rocky Mountain Forest and Range Experiment Station

The Rocky Mountain Station is one of eight regional experiment stations, plus the Forest Products Laboratory and the Washington Office Staff, that make up the Forest Service research organization.

RESEARCH FOCUS

Research programs at the Rocky Mountain Station are coordinated with area universities and with other institutions. Many studies are conducted on a cooperative basis to accelerate solutions to problems involving range, water, wildlife and fish habitat, human and community development, timber, recreation, protection, and multiresource evaluation.

RESEARCH LOCATIONS

Research Work Units of the Rocky Mountain Station are operated in cooperation with universities in the following cities:

Albuquerque, New Mexico
Flagstaff, Arizona
Fort Collins, Colorado*
Laramie, Wyoming
Lincoln, Nebraska
Rapid City, South Dakota
Tempe, Arizona

*Station Headquarters: 240 W. Prospect St., Fort Collins, CO 80526